Escola Tècnica Superior d'Enginyeria Industrial de Barcelona
UNIVERSITAT POLITÈCNICA DE CATALUNYA

FINAL MASTER THESIS

Design and Manufacturing of a Test Rig to Measure Brake Components' Fluid Consumption

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1. Preface

1.1. Origin of the project

Fluid consumption tests are very common and frequently required by most automotive customers such as OEMs. However, this type of measurement involves a considerably time-consuming process. This is the reason why, from the Braking Systems department of Applus+ IDIADA, it has been observed that designing and manufacturing a bespoke test rig can be very helpful in order to reduce the amount of time required to conduct the tests and, furthermore, improve the accuracy of the measurements. The project has been undertaken as an *ideada*, i.e. an internal project funded through the Innovation department of Applus+ IDIADA with the collaboration of Universitat Politècnica de Catalunya.

1.2. Motivation

The main motivation is the opportunity of being involved within an automotive company, thus having the chance of understanding the different parts that compound a braking system, as well as designing and leading the manufacturing of a test rig aimed at measuring fluid consumption.

Last but not least, the chance of developing the final master thesis with Applus+ IDIADA is a great opportunity to gain experience and learn from experts of a big company leader in the field of automotive engineering.

1.3. Previous requirements

The previous requirements to develop the Final Master Thesis wit Applus+IDIADA are listed below:

- Knowledge of automotive braking systems
- CAD/CAE software
- Fluent in English, written and spoken
- University student with the 50% of the credits achieved

2. Introduction

Brake pedal feel is very important in modern passenger car braking systems. This feeling is determined by the relationship between the force applied on the pedal by the driver's foot, the movement of the pedal and the deceleration of the vehicle. It is such an important parameter in terms of the driver interface that the movement and deformation of the component parts of the system, which affects the force/travel relationship, must always be estimated or predicted at the design stage, or measured from previous similar installations. This last way is chosen by Applus+ IDIADA to perform these measurements.

The project is carried out in Applus+ IDIADA facilities as an *ideada* internal project. The first part of the project is to define the techniques and the different parts to design and manufacture the test rig. The main objective of this part is to understand the problem and select the main components to build the rig in order to determine different values of fluid consumption by each part of the brake system. These components should be dimensioned to withstand specifications and ensure the proper functioning of the test.

Once the materials are selected, the second step will be the design of the test rig, taking into account the materials and components selected on the first step. The test rig will be designed with CAD software.

The last step will be the assembly of the CAD design and the different elements that compound the hydraulic circuit to carry out the test. Therefore, this design is going to be tested and validated with different configurations of brakes and different elements such as hoses, pipes, calipers, etc.

Finally, after performing validation tests, the test rig will be used in the brakes laboratory to carry out different absorption brake tests, as part of commercially-focused projects conducted by Applus+ IDIADA.

2.1. Objectives of the project

- Study and investigate which are the main needs associated to the manufacturing of the absorption test rig.
- Design an absorption test rig capable of being controlled by the IDIADA's own data acquisition system for brake activities.
- Select all materials and parts, from components to sensors. It is of special interest to understand the needs of the volumetric transducer.
- Manufacture the absorption test rig and coordinate the software development.
- Validate the absorption test rig through the measurement of different brake components, correlating the results with supplier's data.

As long term goals by Applus+ IDIADA:

- Sell this new service to the OEMs; it is of special interest both for benchmarking and development activities.
- Gain basic knowledge on volumetric measurements to be applied on other vehicle testing.
- Gather volumetric absorptions of some key foundation brakes, thus creating an internal database.

2.2. Scope of the project

The scope of the project is to design the test rig considering only the parts that work with brake fluid. Therefore, the pedal and the brake booster are not taken into consideration for the design since there is no absorption involved.

The test rig will be designed as a mobile device to allow manoeuvrability with the purpose of making the accessibility easier to perform the tests directly on-vehicle. This function is aimed at preventing to disassemble the whole brake system in order to measure the absorption of certain components such as pipes.

3. State-of-the-art

As explained before, the fluid consumption is very important to determine the pedal feeling and for this reason, the different volumetric absorptions need to be measured. Different methods are used to characterize the pedal feel; they are detailed below.

The fluid absorptions of the different parts that form the braking system have an impact on the brake pedal feeling. For instance, an (often-forgotten) example is the effect of the hoses;(Antanaitis, Riefe, & Sanford, 2010) **[1]**, determine the fluid consumption of the hoses (as per the method shown in Figure 3.1) and analyze their influence on the pedal feeling. The measurement is conducted independently of the rest of the braking parts.

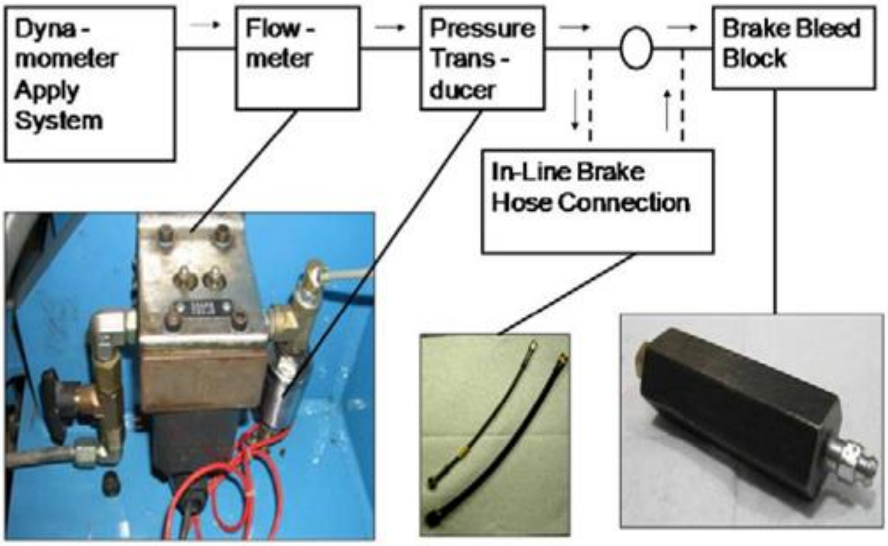


Figure 3.1 Hoses fluid consumption test set-up scheme [1]

The test is performed at different conditions of temperature and pressure levels. The absorptions values obtained from the hoses contribute to the overall pedal feeling of the vehicle.

Hon Pin reports another method. This thesis is focused on the influence of the pedal feeling on the braking effectiveness. In this case, different assumptions are made in order to characterize the different brake parts that influence the pedal feel, such as the master cylinder, the vacuum booster or the caliper/pads assembly [2].

A deeper literature review leads to conclude that generally the adopted approach and methodology to study the pedal feel is detailed below:

- Investigate the parameters of each brake component by either measuring the components (drawings or dismantled components). The value of the stiffness of each internal component is to be examined in detail.

- Investigation of linear and nonlinear components such as the measurement of spring forces and the force-displacement relationship of the elastomeric material. This part of the research will be done on a brake system test rig to investigate the different brake component characteristics.

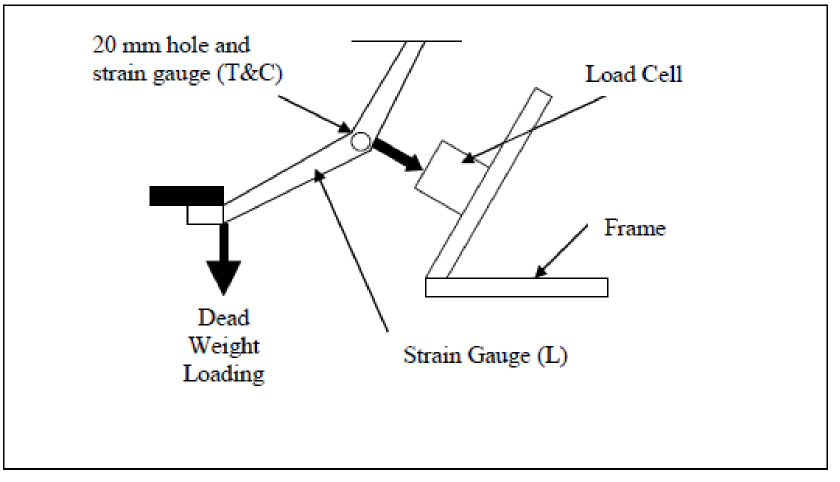


Figure 3.2 Test rig scheme **[2]**

- Study of the results using a computer-based simulation model. This model must have a high accuracy in order to have the result with the minimum error of lecture.

Finally, the pedal feeling measurement can also be determined implying the two different phases showed below (Dairou, 2015) **[3]:**

- Modeling of brake pedal feeling in order to understand the relationship between brake design parameters and brake pedal feel.

- Identification of customers' preferences around brake pedal feeling in order to tune different brake parameters and thus meet their expectations.

These three methods to characterize the pedal feeling –in special the first one (Antanaitis, Riefe, & Sanford, 2010) **[1]** – are meant to be incorporated during the project.

4. Brake system main components

Before the start of the project, the different main parts that form a brake system are briefly presented. The different mechanical and hydraulic components are shown in Figure 4.1.

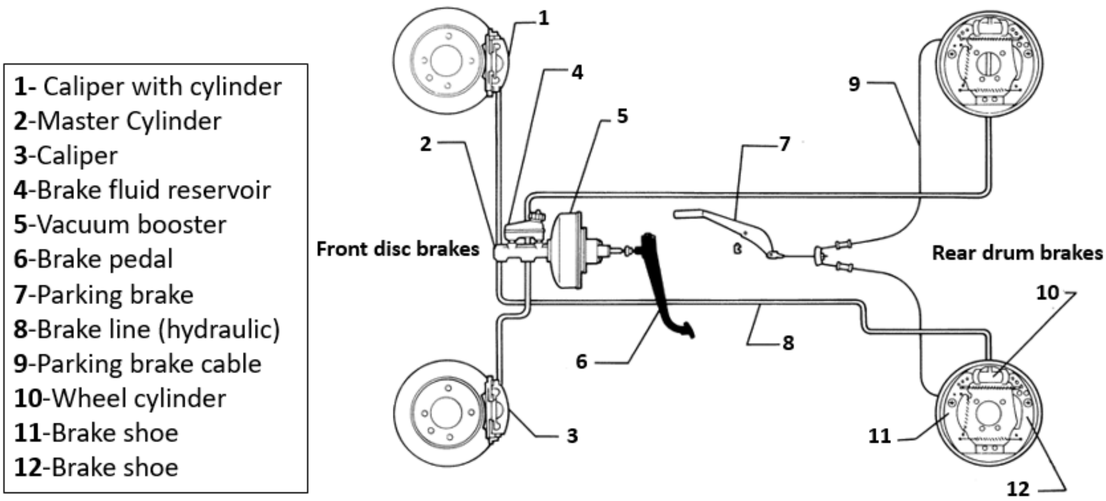


Figure 4.1 Schematic view of a standard dual-diagonal brake system

4.1.1. Pedal

The pedal is the interface between the driver and the braking system. An important parameter of this part is the pedal ratio. This ratio is the lever ratio or the measure of mechanical advantage provided by the pedal. It can be calculated using the expression that is shown in Figure 4.2 that depends of the pedal configuration.

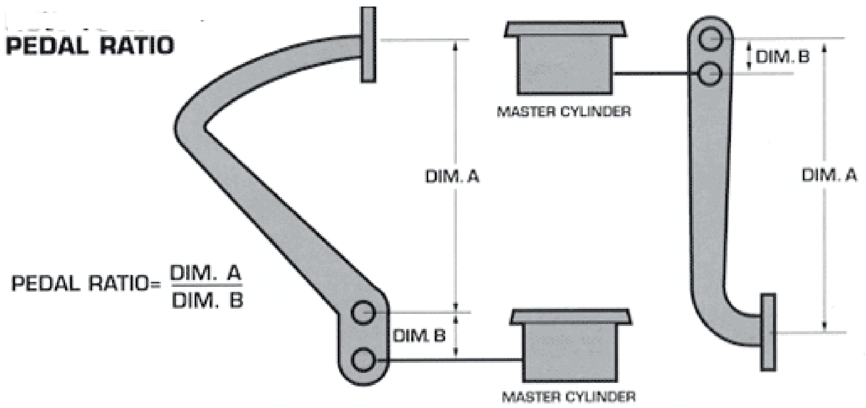


Figure 4.2 Pedal ratio

Depending on the ratio value, the driver must perform more or less force to stop the vehicle under the same conditions.

4.1.2. Booster

The booster (vacuum servo) is a component used in the braking system to assist the driver by decreasing the brake pedal effort. The operating principle is based on creating a depression, which generates a vacuum when the engine valve is open, causing the membrane movement in order to reduce the effort of the driver when pushes the pedal. The engine valve is closed when the driver does not brake. A simple scheme about the booster is shown in Figure 4.3.

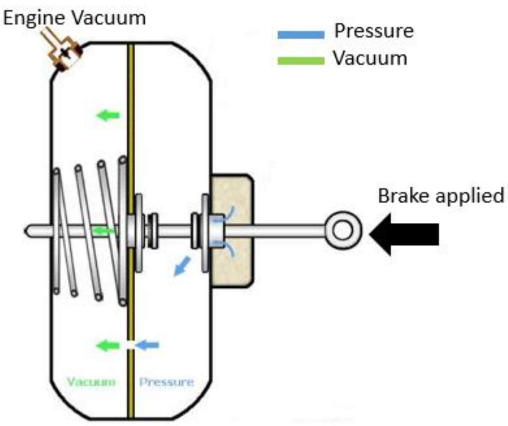


Figure 4.3 Booster working principle scheme

4.1.3. Master Cylinder

The master cylinder is a control device that converts non-hydraulic pressure (from the booster) into hydraulic pressure. It consists of the reservoir tank, which contains the brake fluid, the piston and cylinder, which generate the hydraulic pressure.

Generally, the master cylinder has two separate hydraulic chambers, creating two separate hydraulic braking circuits (primary and secondary) as a safety solution. If one of these circuits becomes inoperative, the other circuit can still function to bring the vehicle to a halt. A scheme of the master cylinder is shown in Figure 4.4.

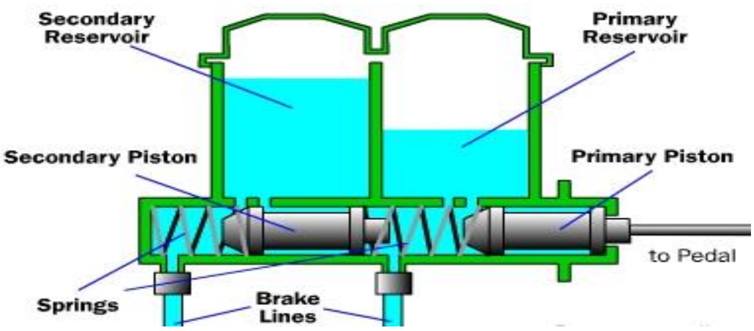


Figure 4.4 Master Cylinder Scheme

The working principle of the master cylinder is simple: when the driver pushes the pedal, the piston movement compresses the spring and moves the cylinder. This movement compresses the fluid, which is distributed among the different foundation brakes, thus clamping the stator (pads) onto the rotor (disc or drum) and stopping the vehicle.

4.1.4. Pipes and hoses

Pipes and hoses are responsible to allow the connection between the master cylinder (and the ABS module) with the front and rear calipers. Generally, pipes are metallic and rigid, while hoses are made of plastic and are flexible.

4.1.5. Calipers

A brake caliper is a shaped metal device on disc brake that you can see through the wheel. They house the brake pads, and their job is to squeeze the pads onto the discs when the compressed fluid presses the pads and has contact with the disc, thus stopping the vehicle.

5. Absorption measurements

In this chapter, a general introduction to the absorption will be made to understand which brake components contribute mostly to the fluid consumption and why these absorptions are that important regarding the brake pedal feeling. Besides, an explanation of the two models currently used by Applus+IDIADA to determine the absorption of fluid will be made.

5.1. Absorption theory

When the driver presses the brakes, the initial brake pedal movement takes up clearances in the system to actuate valves in the master cylinder and servo, and moves the pads or linings into contact with the disc or drum. Then, mechanical loading, thermal loading, internal hydraulic pressure and wear cause a deformation and deflection of the actuation system components, which can only be accommodated by further movement of the brake pedal. The part of this extra movement, which is directly caused by deformation of the hydraulic components under hydraulic pressure, is called *fluid consumption*, and affects the relationship between the course of the pedal brake and the hydraulic pressure generated. (Andrew Day, 2014) **[4].**

In the following chapters, the absorption of each brake system element is explained to understand this phenomenon and the importance on the pedal feeling.

5.1.1. Booster vaccum

This element is very important to determine the brake pedal feel of the driver. This component does not consume fluid but should be taken into consideration. This part is the booster; where the boost ratio (and ultimately the knee point) directly influences the pedal force required to generate the needed line pressure in the brake actuation system. Additionally, other components in a vacuum booster affect the relationship between the pedal force and the line pressure, and thus the pedal feel. Typically, around 20N, pedal force should start to generate boost assistance, and if this minimum force is higher or the brake pedal has to move too much, the result may be poor pedal feel. Once the pedal force exceeds the threshold force, the vacuum servo starts to boost the hydraulic line pressure (jump in) (Andrew Day, 2014) **[4].** An example of booster characterization is shown in Figure 5.1.

The *"jump in"* is the value of pressure respect pedal force that will determine when the booster start giving brake assist. As commented before, this is an important parameter to determine the pedal feel.

On the other hand, the *"knee point"* is a critical situation because it happens when the booster stops giving brake assistance. In this case, when the driver pushes the pedal with all of his force, the booster saturates and reaches its maximum attendance.

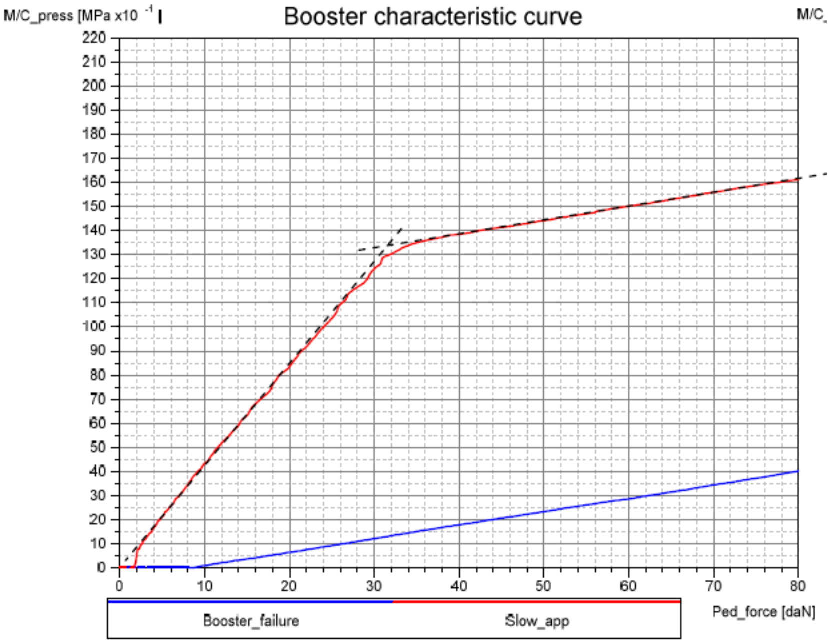


Figure 5.1 Booster characteristic curve

5.1.2. Master cylinder bore

When a pressure is applied on the master cylinder, this suffers a radial expansion. This radial expansion depends of the material of the master cylinder, and depending of the value of this radial expansion the fluid consumption will vary. A fluid consumption example depending on the master cylinder material is shown in Table 5.1.

Material	Cast Iron	Steel	Aluminium Alloy
Bore diameter (mm)	20.64	20.64	20.64
Wall thickness (mm)	5	3	7
Young's modulus (GPa)	175	200	75
Poisson's ratio	0.25	0.29	0.33
Hydraulic pressure (MPa)	10	10	10
Radial expansion (mm)	0.0013	0.0017	0.0028
c_{mc} (mm^3/MPa) (assuming a 25 mm stroke)	0.22	0.27	0.46
Fluid 'consumption' at 10 MPa (100 bar) (mm^3)	2.2	2.7	4.6

Table 5.1 Comparison of the Estimated Expansion of the Bore of different MC designs and materials [4]

As shown in the table above, at the same value of pressure and bore diameter and varying the wall thickness and the material, the fluid consumption is different in each case. Therefore, the fluid consumption in this case depends on the material and the design. A previous study might be made to ensure the minimum fluid consumption in order to improve the pedal feeling.

5.1.3. Slave cylinder and Seal deformation

Slave cylinders and pistons provide the actuation force at the foundation brake (disc or drum) in a hydraulic braking system. In drum brakes the slave piston acts directly on the shoe tip, and in disc brakes there may be one, two or more pistons acting on each pad. In these cases, there are a relation between the applied hydraulic pressure and the actuation force generated by the slave cylinder piston. As with the master cylinder the fluid consumption in a slave cylinder arises from deformation of the bore and deflection of the piston seals (Day, 2014) **[4]**. Therefore, the fluid consumption in this case is like master cylinder, caused by expansion and deformation of the slave cylinder.

5.1.4. Brake pad compression, deflection and wear

The pad is compressed when a pressure is applied. This fact determines the brake pad compression. The displacement of the pads when a certain pressure is applied affects the fluid consumption due to the pad deformation. This value will depend of the pad material and the applied pressure. A scheme is shown in Figure 5.2.

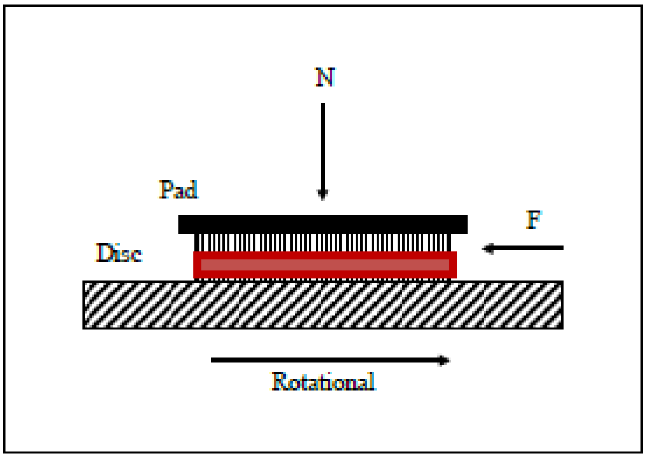


Figure 5.2 Pad compression scheme [4]

Red area shows the compression of the pad. Due to the movement, more fluid will be needed to generate the same braking pressure. This compression causes the increase of fluid consumption.

The same idea can be used to describe the wear of the pad. The pad loses material during his service life, increasing the distance between the disc and the pad. This difference of distance affects directly to the fluid consumption because more fluid will be required to allow the contact between these parts.

Finally, the deflection also affects the amount of fluid given that the contact geometry between the pad and the rotor is modified; the fluid might compensate the new gap by using a different amount of liquid.

5.1.5. Hoses, pipes and ABS module

Hydraulic brake lines are thick-walled steel tubes, and thick-walled composite flexible hoses made from reinforced rubber where flexibility is required to connect parts that move relative to each other. In this case, the composite hoses have much higher flexibility and in consequence, a higher value of fluid consumption produced by their expansion. For example, for a typical brake line at 100 bar the fluid consumption can be around 1,5 mm^3 per meter length. Hence, the fluid consumption in a pipe is around 0.15 $mm^3/MPa \cdot m$, while in a flexible hose is around 30 $mm^3/MPa \cdot m$ (Day, 2014) **[4]**. It can be observed that the flexure of material have more fluid consumption than a rigid pipe due to the different material (more porosity).

In the other hand, the ABS module is designed to be neutral in terms of braking system performance including pedal feel when they are not operational. During operational they are designed to minimize transient dynamic effects (pulsing) on the brake pedal.

5.2. Current measurement methods

Currently, Applus+ IDIADA uses different methods to measure the volumetric absorption of the braking system components. All of these methods are valid and equally accurate, but there are differences in the implementation process and assumptions that are worth pointing out.

5.2.1. Method 1

The stroke and pedal effort are measured statically (with the vehicle in the workshop) under different conditions: both front and rear brake circuits are either opened (thus leaking), closed or kept as in service, thus making up to nine combinations. These combinations are performed due to customer specifications and the information is confidential. The final front and rear circuits' consumption (volume) is deducted based on the measured pedal travel; to do so, the calculation takes into account (among others) the pedal ratio, the diameter of the master cylinder and the efficiencies of the brake pedal box and the master cylinder. These parameters are either measured on-vehicle or estimated, thus converting the final absorption figure in an actual estimation too. An example of the different combinations and its results is shown in Figure 5.3.

	FRONT & REAR CIRCUIT COMBINATIONS																	
	1		2		8		3		4		5		9		6		7	
Circuit	FR	RR	FR	RR	FR	RR	FR	RR	FR	RR	FR	RR	FR	RR	FR	RR	FR	RR
Position	U	U	U	S	U	P	S	U	S	S	S	P	P	U	P	S	P	P
Pedal stroke (mm) At 70daN	165,60		156,58		116,36		160,72		147,71		100,57		98,67		83,31		40,10	

U = Unplugged, S = Service y P = Plugged

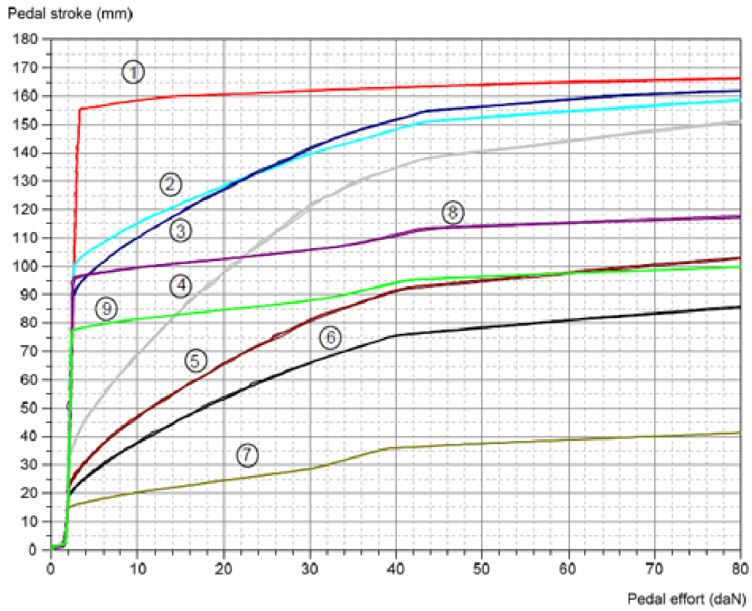


Figure 5.3 Summary of the main results - Method 1

This method has different vantages and disadvantages:

Vantages:

- Allows different brake circuit combinations (unplugged, service, plugged for both primary and secondary circuits), thus being redundant and making sure of the accuracy of the measurement.

Disadvantages:

- The measurement is conducted as pedal stroke, obviating the stroke of the master cylinder, which has to be calculated (certain pedal box and master cylinder efficiencies are either omitted or estimated, what brings uncertainty to the results)

5.2.2. Method 2

The test is divided in four different steps of constant pressure as measured in the master cylinder, giving the component absorption for each pressure level. Volume measurements are calculated by multiplying the (measured) master cylinder stroke and its inner area.

The data is taken from master cylinder pressure and master cylinder stroke at a constant pressure range and as close as possible to each specified pressure level. The measurements of each part are made in different steps as shown in the list below:

1. <u>Baseline:</u> Includes all hydraulic braking systems.

2. <u>Wheel calipers:</u> FL, FR, RL, RR are cut sequentially in order to isolate every single caliper.

3. <u>Hoses:</u> All four hoses are set at the same time, thus getting the consumption of all hoses.

4. <u>Rest of components:</u> Master Cylinder, ABS, pipes, pump, etc.

As shown in Table 5.2, the sum of the different steps measurements gives the total (baseline) absorption in the different defined pressures.

MC Press [bar]	10		30		70		100	
Baseline (mm3)	3075,5	100%	5134,6	100%	8404	100%	10524,1	100%
FL_caliper (mm3)	466,3	30%	1128,7	44%	2010,6	48%	2541,6	48%
FR_caliper (mm3)	462,4		1136		1991,2		2532,5	
RL_caliper (mm3)	318,6	19%	511,3	18%	829,9	19%	1033,5	19%
RR_caliper (mm3)	269		405,7		784,1		977,5	
Hoses (mm3)	72,3	2%	140,1	3%	354,8	4%	652,6	6%
MC /pipes (mm3)	1487	48%	1821,8	35%	2433,3	29%	2786,4	26%

Table 5.2 Summary results - Method 2

A graph has made to analyze the different values of absorption obtained in different parts and pressure values. This summary of results is shown in Figure 5.4.

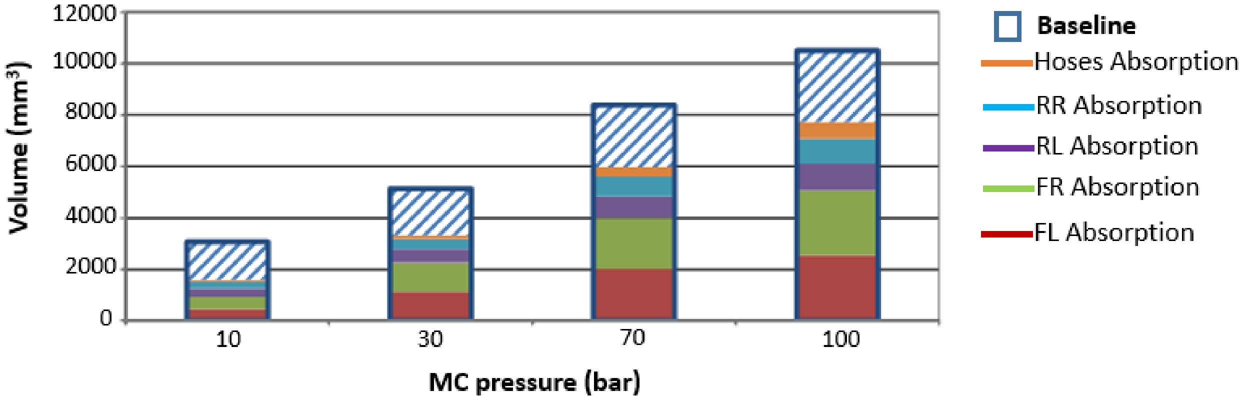


Figure 5.4 Summary results graph – Method 2

As in method 1, this method also has different vantages and disadvantages that are listed below:

Vantages:

- Each brake component (e.g. caliper, hose, pipe, etc.) can be isolated and, therefore, its absorption can be known. Method 1, on the contrary, just characterized the whole (primary or secondary) circuit.
- Stroke of the master cylinder is measured directly, thus improving accuracy with respect to the first method – no assumptions need to be taken with respect to the pedal ratio or the different system efficiencies.

Disadvantages:

- Absorptions are not redundant, thus giving certain uncertainty to the result. To reduce it, it is important to make sure that all measurements are conducted under very stable pressure levels.

5.2.3. Conclusions

After comparing both methods currently used, it can be determined that a mixture of both methods could be the best solution:

- Method 1: redundancy of the measurements.
- Method 2:
    - Possibility of isolating the brake components.
    - Better accuracy by measuring directly the master cylinder stroke.

For this reason, it is important to create a bespoke test rig that overcomes all drawbacks currently present in both methods.

6. Test Rig proposal

In the following section, a solution for the volumetric absorption test rig is proposed. This design includes parts built in purpose (previously designed in-house) and components carefully selected from different providers.

6.1. Design and Components scheme

The components selected to perform the test rig are listed and detailed below:

- Actuator: This part will be responsible for transmitting the force to achieve the desired value of pressure in the component to be measured. This actuator simulates the action of the driver on the pedal.

- Pump (Master Cylinder): This part will compress the fluid from the force that transmits the actuator.

- Filter: The brake liquid needs to be filtered in order to protect the flow volumetric sensor. This part add an extra fluid absorption and will be considered during the tests.

- Flow meter: Volumetric sensor aimed at controlling the movement of the brake fluid. Besides, this sensor will be used to calculate the final fluid absorption of the tested brake component.

- Pressure transducer: This sensor is meant to control the pressure during the test.

- Pipes: A pipe system is to be used to link the different rig components. It is very important to determine the length to control the fluid consumption before the final measurement.

- Brake bleed system: This device will be installed to remove the air from the brake system.

- Position sensor: This device will control the position of the master cylinder to avoid its end of stroke, stopping the test when a defined value of stroke will be achieved.

- Control system: Specific software will be designed in-house to control and perform the test. The control must respect the restrictions and should be designed to apply an accurate pressure profile throughout the test.

6.2. Assumptions and difficulties

Under normal driving conditions, the applied pressure on the brake discs is around 15 bar and 30 bar for the drum disc in normal driving conditions. In each case, the maximum pressure that will be achieved is 100 bar during some proving ground tests. However, some customers wants to perform test until 200 bar. For this reason, the test rig will be designed thinking that the maximum applied pressure that will be applied in several cases is 200 bar. For this reason, all components such as the flow meter, the pressure transducer, the pump and actuator must be dimensioned and selected to hold this maximum pressure.

On the other hand, to achieve such a high pressure, a master cylinder is to be used whose internal rod is to be pushed by means of a lever, actuated on the other end by a linear actuator. Taking advantage of the lever arm (ratio), the necessary load to be applied by the actuator is considerably reduced, and the desired high pressure can be achieved in the opposite end with a small master cylinder diameter.

The main difficulty must be the correct volume measurement. In this type of test the volumetric flow rate is very low, given that the brake liquid is ultimately compressed. Therefore, the flow meter must be able to measure those minimum flow rates at very high pressures. For this reason, the flow meter must be accurate enough; before the selection of this component, a previous test is to be conducted to determine the flow rates that the actual test rig will deal with.

6.2.1. Previous tests

A previous prototype using a lever is built to perform the mentioned tests aimed at understanding the flow rate values expected to obtain in the actual test rig. This device has a structural support, where all the components are assembled. It uses a lever connected to a manually-operated actuator fixed to the master cylinder, which will be used in the final test rig. On the selected master cylinder, different sensors are installed to control its stroke and the final fluid pressure (using a pressure sensor). The previous prototype is shown in Figure 6.1.

1- Actuator

2- Lever

3- Transducer

4- Master Cylinder

5- Test simple

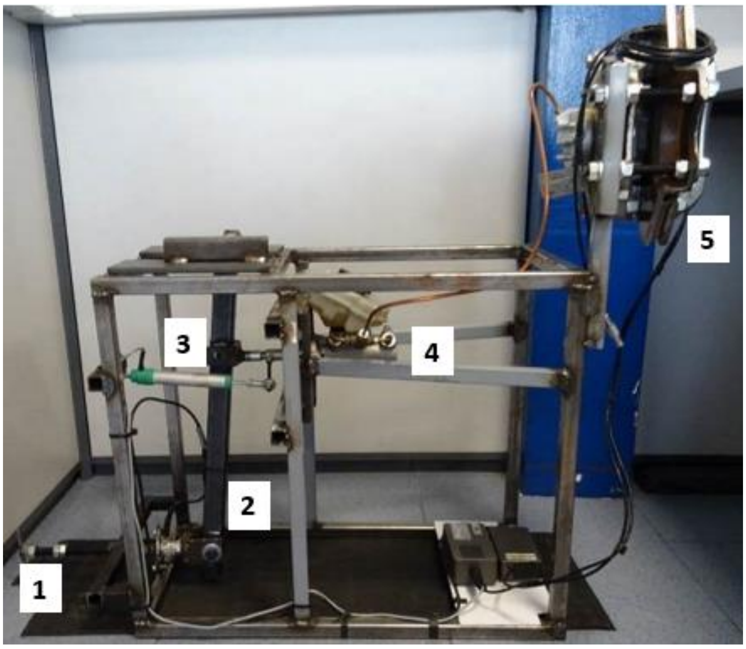


Figure 6.1 Previous prototype to perform the tests

In Figure 6.2, detailed areas from the prototype are shown:

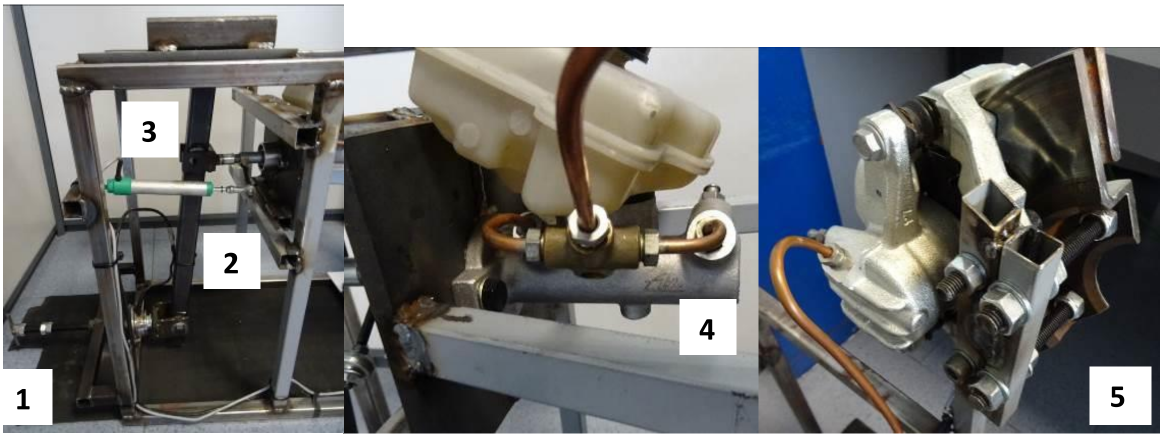


Figure 6.2 Previous prototype detailed areas

In order to select the appropriated flow meter, a previous test will be performed to determine the minimum flow velocity. The flow will be determined deriving as a function of time the master cylinder displacement and multiplying for the master cylinder section. An important parameter is the pressure evolution versus the stroke that will be plotted, as shown in Figure 6.3.

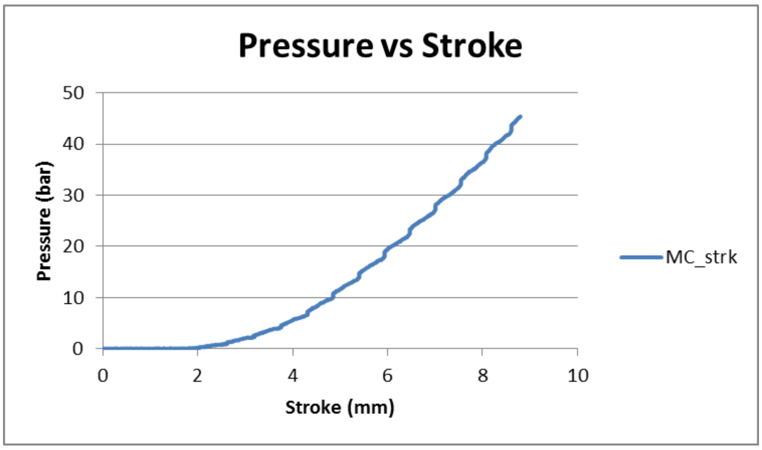


Figure 6.3 Previous test - Pressure versus Stroke

As shown in the figure above, the pressure increases politropically when the cylinder is moving.

Another parameter to consider is the evolution of the flow with respect to time in order to ensure the minimum flow. The results are shown in Figure 6.4.

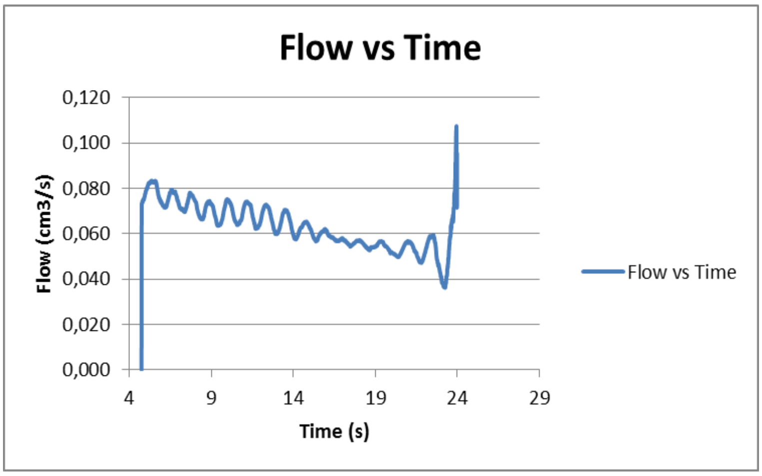


Figure 6.4 Previous test – Flow versus Time

The oscillation of the results is consequence of the actuation system to move the lever. In this case, a manually-operated actuator fixed to the master cylinder is used to move the lever and the oscillation is due to this type of actuation.

The fluid grows rapidly up to 0,080 cm^3/s and then decreases up to 0,050 cm^3/s. This range should be ensured for the flow meter to read the correct value and ensure the final result of the test.

The problem that has observed is the stability of the system. As shown in the previous figures, the results are not linear due to the lever system designed for these previous tests. To reduce this parameter three-actuation options will be evaluated:

- Linear actuator
- Pump
- Actuator and Lever

Next section shows and discusses the equipment selection from the previous tests shown in this section.

6.3. Equipment selection

6.3.1. Sensors

Pressure sensor and flow meter will be selected from previous testing shown in section 6.2.1.

The first selection will be the pressure sensor up to 200bar, which must read values with very little precision error. The model of this sensor is the UNIK 5000 (General Electric) that has a work range from 70mbar to 700bar, an precision ±0,04% and an operating temperature range from -55 to 125ºC. The frequency response will be 5kHz. With this device the pressure will be monitored and controlled with the minimum error.

On the other hand, the flow meter is more complicated to choose because the main problem is the Q_{min} (cm^3/s). The provider offers two possibilities to install in this type of applications. As explained previously, the main problem is the minimum flow and the lecture accuracy. Some specifications are shown in Table 6.1.

Model	Vol. measurement (ml/pulse)	Q_{max} (cm^3/s)	Q_{min} (cm^3/s)
VSI 0.1	0,00625	166,67	0,16
VSI 0.02	0,00125	33,33	0,033

Table 6.1 Flow meters specification

Analyzing the previous tests and the specifications of the provider (see Figure 6.5), the selected flow meter is the VSI0.02 model. This selection is because in the test the minimum flow configured on VSI0.1 will not be reached. The negative part of this selection is the limited range of temperatures, but in this case the test will be carried out at room temperature. Besides, this device needs a filter to ensure the correct operation of the flow meter.

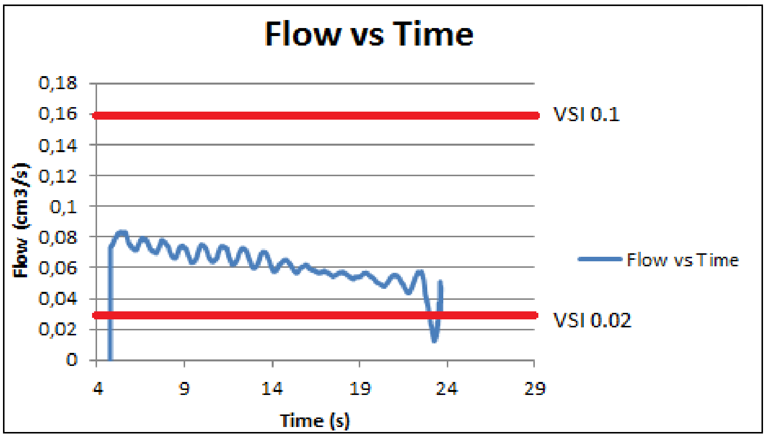


Figure 6.5 Flow meter selection - Previous test

A filter must be set before the flow meter to ensure the correct function of the flow meter. The measure of the filter mesh must be 10µm, specified by the flow meter provider. In this case, a mesh of 7µm will be set up because is the only option that the provider offers us and satisfy the flow meter restrictions. The filter specifications are shown in Table 6.2.

Part	Provider	Model	Configuration	Mesh (µm)
Filter	Swagelok	SS-4F-K4-7	T	7

Table 6.2 Filter specifications

6.3.2. Pump, bleeder pump and workbench

The pump (Master Cylinder) that has been selected is from a real car. The model is a Citroen Saxo and the main specifications of this model are shown in Table 6.3.

Part	$Ø_{piston}$ (mm)	Nº Channels	Ch 1Stroke (mm)	Ch 2 Stroke (mm)
Master Cylinder	19	2	10	10

Table 6.3 Master Cylinder Specifications

A bleeder pump has been selected to remove the existing air in the pipes. The system is based on a pump that inhales the air.

Finally, a workbench has been selected to install all the components above the table. This part will be modified extracting one of the drawers. The selected model is Facom 2000.BB1M3 and the dimensions of the main plane are shown in Table 6.4.

Part	Length (mm)	Width (mm)	Height (mm)
Facom 2000.BB1M3	2000	750	850

Table 6.4 Workbench specifications

6.3.3. Actuator

The actuator should be selected to achieve the maximum desired value of pressure (200 bar) taking into account the selected master cylinder.

As explained before, three options have been studied to transmit the force to the pump. Then, different actuation methods are shown in the list below:

- Linear actuator: This is the best option to transfer the load steadily (without oscillations) to the master cylinder. The main problem is the stroke, which is difficult to calculate and measure to obtain the desired value of pressure in each step. In addition, the force value to achieve the desired pressure is very high.

- Pump: The second option is a pump that moving the fluid transmits the load to the master cylinder. The problems are founding a small pump capable of working with brake fluid and transmitting the required force to the master cylinder.

- Linear actuator + lever: As shown in the previous tests, this system produces oscillations on the final result. It is a known and simple method that it is easy to build and install. The problem is found a control method to reduce the oscillations and provide stability.

A research has been done to determine the best option to transmit the force. After discussing with different pump suppliers, this option has been dismissed because there is not any pump that meets the application requirements. On the other hand, the option to use a linear actuator without a lever has been dismissed because the relationship between the actuator stroke and the flow is difficult to determine. For example, with a small displacement of the actuator stroke or of the lever, the flow can grow up suddenly, without following a particular relationship. In addition, the necessary force value to achieve the desired pressure of 200 bar would be very high.

Therefore, the selected option has been the last one, i.e. the design and manufacture of a system that uses an actuator and a lever to transmit the force to the master cylinder. The actuator and the lever are dimensioned in order to achieve the desired value of maximum pressure. A ratio (simulating the pedal ratio) is determined to select the correct actuator. Besides, the stroke of the master cylinder has to be taken into account for sizing the system. The maximum master cylinder external stroke (taking into account the junction with the lever) is 34mm. Fixing the pump stroke, linear actuator stroke and using trigonometry, the dimension of the actuator is set. In addition, the needed force to achieve the desired value has to be determined. A scheme of the system is shown in Figure 6.6.

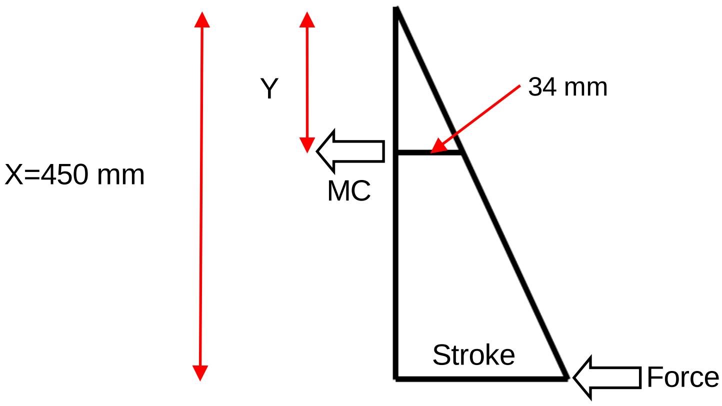


Figure 6.6 Calculation scheme

Different models of actuator with different specifications have been compared to select the best option to install on the test rig according to the restrictions showed in Figure 6.6. The compared models are actuated by an electric rotary engine that moves a cylinder fixed on a ball screw. The results are shown in Table 6.5.

Actuator specifications			Design restrictions		Calculated values			
Model	Force [N]	Stroke [mm]	P.stroke [mm]	Value X [mm]	Value Y [mm]	Ratio	MC Force [N]	Pressure [bar]
SKF-341-1611	2000	200	34	450	76,5	5,88	11764,7	414,9
SKF-341-1627	2000	300	34	450	51	8,82	17647,1	622,4
SKF-764-3483	500	300	34	450	51	8,82	4411,8	155,6
SKF-885-5312	2300	305	34	450	50,2	8,97	20632,4	727,7
SKF-341-1605	2000	150	34	450	102,0	4,41	8823,5	311,2
SKF-764-3421	2000	100	34	450	153,0	2,94	5882,4	207,5
SKF-341-1528	2000	100	34	450	153,0	2,94	5882,4	207,5

Table 6.5 Linear actuator selection

Models SKF-764-3421 and SKF-341-1528 are the best option. Both models have the same stroke and the same force. The pedal ratio, deemed as acceptable, is 2.94. The actuator will be controlled in function of the desired pressure, demanding the required force available for achieve the pressure on the master cylinder. A specific software will be designed to control the actuator and the entire bench.

6.3.4. List of components

As a general view, all selected components are listed in Table 6.6.

Device	Brand	Model	Comments
Flow meter	VSE	VSI 0.02	-
Pressure sensor	GE	UNIK 5000	-
Transducer	GEFRAN	PZ-34-A-150	-
Filter	Swagelok	SS-4F-K4-7	T configuration
Actuator	SKF	764-3421	Load = 2000 N
Workbench	Facom	2000.BB1M3	-
Pump (MC)	TRW	PMD397	Bore Ø = 19mm
Bleeder Pump	Ate	740307	-

Table 6.6 List of materials summary

With the listed components and parts the test rig will be designed and the components can be ordered to the different providers.

7. Test rig design

Different parts are to be designed to build the test rig. These parts, listed below, are designed on the basis of the selected workbench:

- Plate base: support of the component that will be tested. The design will have some treated holes to fix the brake component.
- Residual tank: part designed to contain the fluid when the test finishes and the parts are disassembled.
- Structural support: In order to make easier the assembly and maintenance of the components that conform the actuation system and the data acquisition, a metallic structure should be designed. The main objective is assembling all the components in this structure and fixing them in the workbench box. The design must take into account the lever length and have to support the weight of all the components.
- Lever: The rigidity of this part is crucial, as the deflection of this part is to be avoided when applying load, thus reducing the error of the data lecture due to lever deformation.

7.1. Base design

The plate base should enable the fixation of the different components that will be tested, supporting them and preventing its movement. On the other hand, the residual tank should be designed to retain the brake liquid and prevent its dispersion. This part has a hole that connects the residual tank and the deposit, carrying fluid through a pipe.

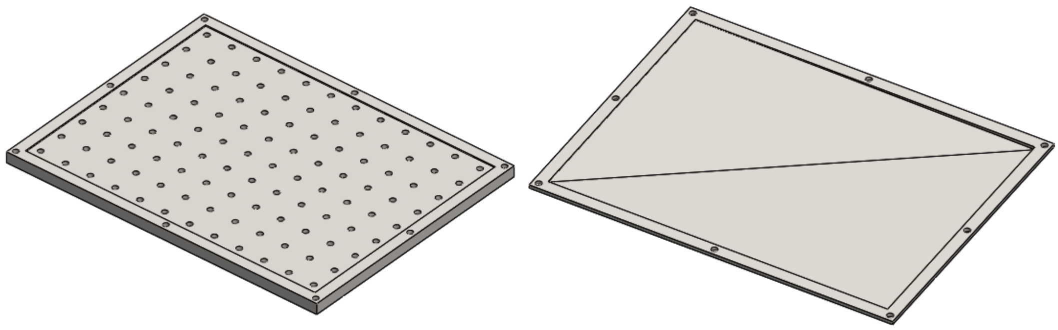


Figure 7.1 Base parts design

The dimensions of these parts are shown in the drawings attached on the annexes.

These designs will be fixed above the workbench in order to prevent the assembly movement and make easier the technician manoeuvrability. The dimensions of the parts should be determined taking into account the test bench width and the installation of a computer to show in situ the test procedure.

7.2. Lever design

7.2.1. Lever 1

The lever should be designed to resist the load solicitation respecting the conditions described in section 6.3.3. The design will be based in a double T profile to reduce the stress and the lever deformation, as that could affect the final test result.

Different lever configurations have been designed and studied in order to select the best solution for the application. The first design that is created is shown hereunder:

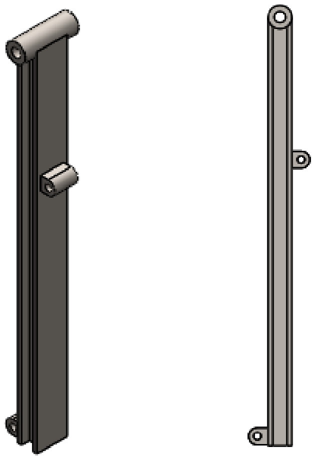


Figure 7.2 Lever first design proposal

The lever main dimensions are shown in Figure 7.3.

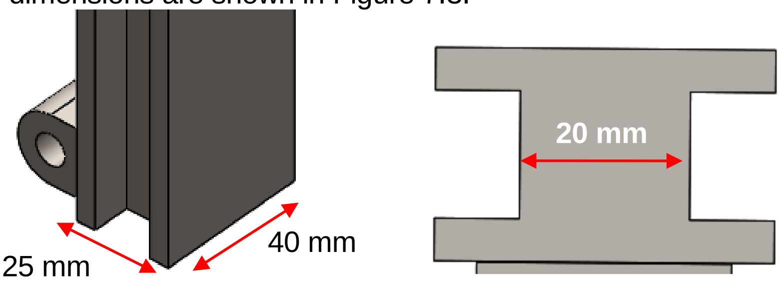


Figure 7.3 Lever 1 main dimensions

The material properties are shown in Table 7.1.

UNE*/SAE	%C	%SI	%MN	Treatment	Yield Strenght (N/mm^2)
F114/1045	0,45	0,4	0,5	Normalized	340

Table 7.1 Material properties

In order to determine if this design is valid, a static simulation using FEM is performed; maximum stress of the bar and maximum deformation are characterized, analysing the critical zones and determining the validation of the part.

7.2.1.1. Simulations

7.2.1.1.1 Assumptions and boundary conditions

This simulation is purely static. The first step is determining the main boundary conditions and the assumptions: fixations, free movement, force application, etc. These assumptions are listed below:

- Displacement: Free movement of the X and Y axes. This boundary condition is referenced on the junction with the structure. This area is shown in Figure 7.4.

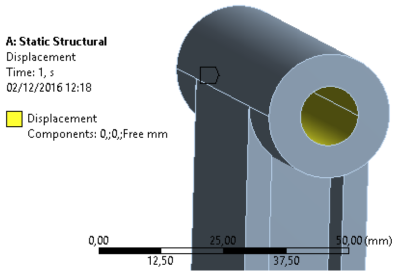


Figure 7.4 Displacement condition

- Fixation: This condition is defined on the junction with the master cylinder. This consideration is defined because the fluid opposes resistance to the master cylinder movement. The fixation area is shown in Figure 7.5.

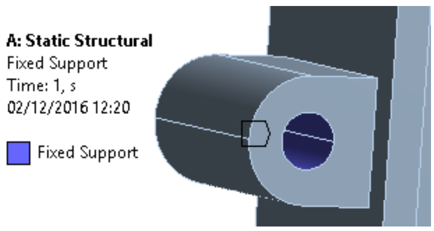


Figure 7.5 Fixed support condition

- Application force: The force is applied in the junction between the actuator and the lever. The force value should be the same that the maximum value given by the actuator (i.e. 2000 N). The application area and the load direction are shown in Figure 7.6.

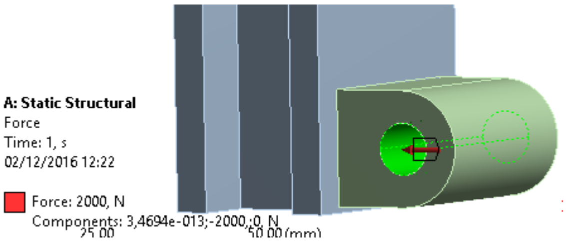


Figure 7.6 Force application

7.2.1.1.2 Mesh

The mesh is the most important part of the analysis. Being a part with different geometries and forms, the best option is to make a hexagonal mesh, as shown in Figure 7.7.

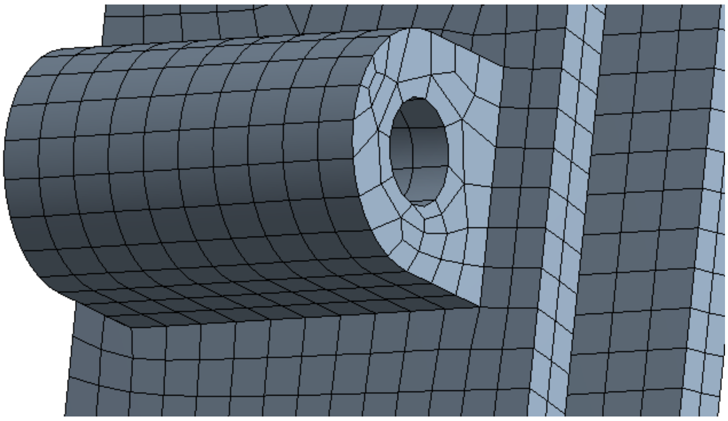


Figure 7.7 Mesh detail

The mesh is hexagonal with a 2mm element dimension. The critical area might be the union between the master cylinder and the lever.

7.2.1.1.3 Results

The assessment criteria chosen for the static simulation are the equivalent (von-Mises) stress and the unitary deformation. The following images show the color map of these results to determine the areas that exhibit more deformation and the location of the maximum stresses.

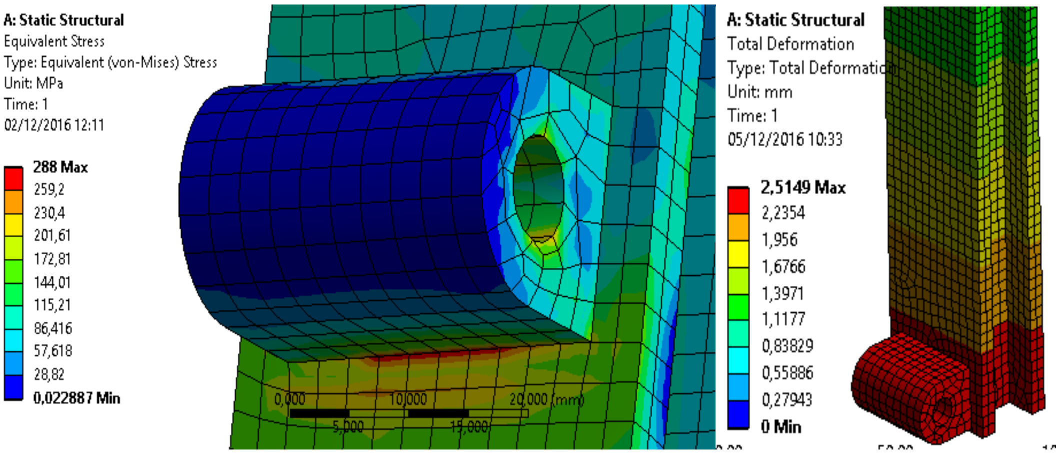


Figure 7.8 Equivalent Stress and deformation results – Lever 1

The results of the simulation for this design are listed hereunder:

Design	Max. Stress (MPa)	Max. Deformation (mm)	Yield Strength (MPa)
Lever 1	288	2,5	340

Table 7.2 Summary of results - Lever 1

As shown in Table 7.2, the maximum stress is very high, and it is near to the yield strength of the material. This stress is located on the union, which is a critical area due to the efforts produced by the load of 2000N. Besides, the deformation is more than the expected. Another design should be done in order to diminish the maximum stress on the zone and make lower the maximum deformation.

7.2.2. Lever 2

The second design has been optimized to reduce the maximum stress and deformation. Reinforcement has been installed on the master cylinder fixation to reduce the maximum stress and make the bar more rigid. The width of the lever is modified, making bigger the profile. Finally, the junction with the actuator has been modified due to package problems. The final design is shown in Figure 7.9.

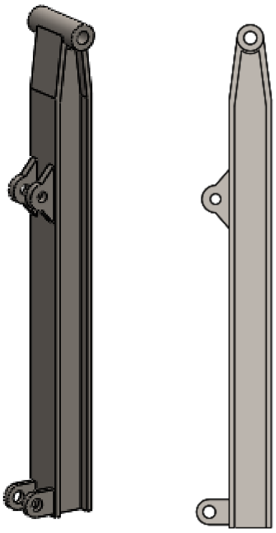


Figure 7.9 Lever 2 design proposal

With this design proposal, the expectation is to achieve the desired values of maximum stress and maximum deformation on the critical area, ensuring the material integrity and making possible the correct development of the tests. The maximum deformation criterion deemed as accepted is 1mm; this is the value that is considered as not affecting the results of the test due to lever deformation.

As explained before, reinforcement should be set up on the master cylinder fixation.

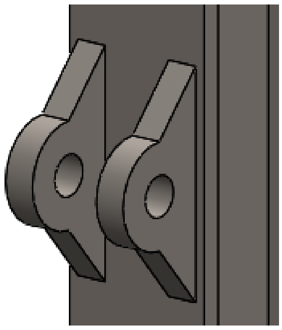


Figure 7.10 Reinforcement

The reinforcement provides more rigidity on this junction, making lower the stresses on the critical area and ensuring that the lever will resist the efforts. The profile dimensions are shown in Figure 7.11.

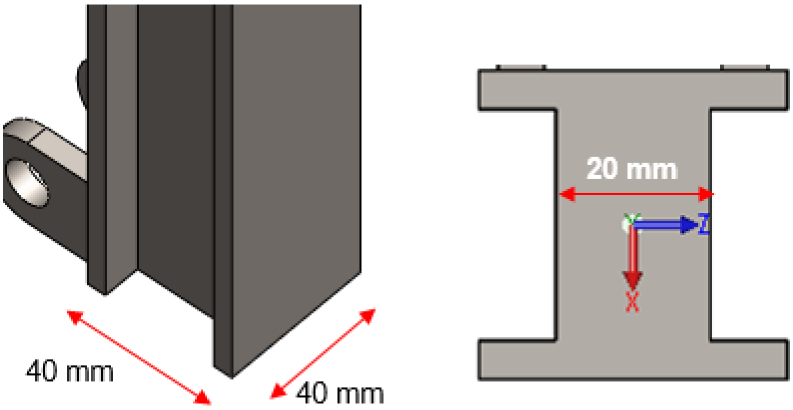


Figure 7.11 Lever 2 profile dimensions

According to the restrictions, the detailed dimensions of the lever are shown the drawings attached on the annexes.

7.2.2.1. Simulations

7.2.2.1.1 Assumptions and boundary conditions

The assumptions of displacement and fixed elements are the same as explained in chapter 7.2.1.1.1. The difference is on the location and actual magnitude of the applied load (Figure 7.12).

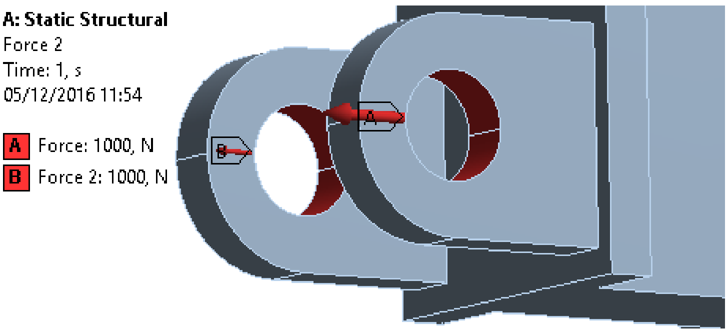


Figure 7.12 Load application - lever 2

The total load should be divided in order to achieve the desired value of load and respect the conditions.

7.2.2.2. Mesh

As explained previously, the mesh quality is very important. The mesh type is the same as in the previous case, adding a mesh control parameter on the reinforcement-lever junction. With this control, the mesh uniformity is improved, minimizing results error.

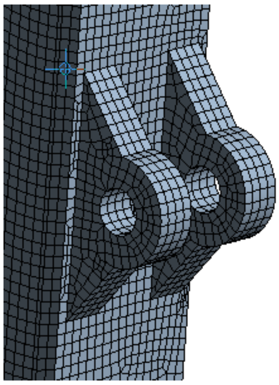


Figure 7.13 Mesh - Lever 2

7.2.2.2.1 Results

As in the previous case (Lever 1), the results are plotted against the equivalent (von-Mises) stress and the total deformation criteria.

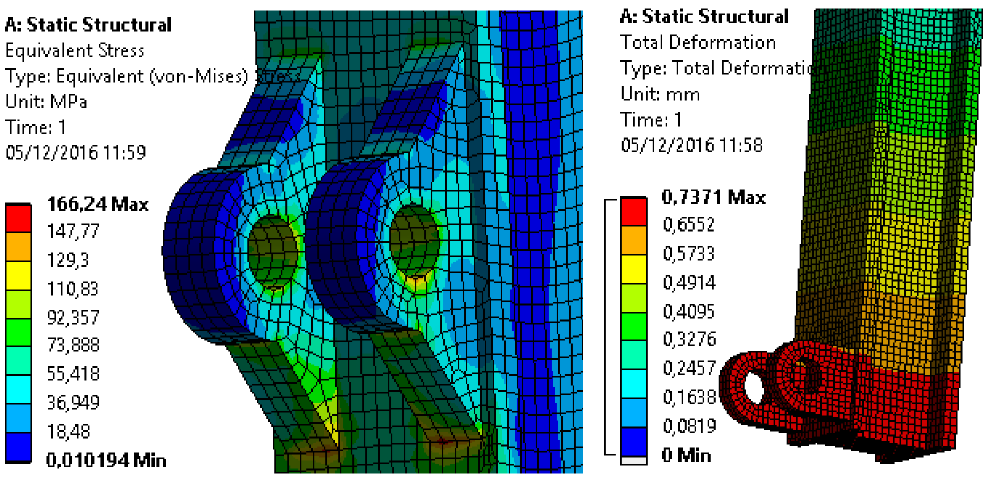


Figure 7.14 Equivalent stress and deformation results - Lever 2

Design	Max. Stress (MPa)	Max. Deformation (mm)	Yield Strength (MPa)
Lever 2	166,2	0,74	340

Table 7.3 Summary of results - Lever 2

As shown in Figure 7.14, the results of the lever 2 are better than Lever 1, reducing until 166 MPa the maximum stress on the critical area, now being an acceptable value. The maximum deformation is still located in the same area but with a minor value (0.74 mm).

7.3. Lever selection

A summary of the simulation results for both proposed lever designs is shown in Table 7.4.

Design	Max. Stress (MPa)	Max. Deformation (mm)	Yield Strength (MPa)
Lever 1	288	2,5	340
Lever 2	166,2	0,74	340

Table 7.4 Summary of results

Analyzing the results, the best option is the second design (Lever 2), given that it exhibits 42.3% less of maximum stress. Besides, the second design has less deformation than the first one, an important parameter to take into account. Therefore, this is the design to be manufactured.

7.4. Structural support

The structural support is to be designed to fit the actuation system, which is formed by the lever, the actuator and the master cylinder. Besides, it should contain the flow meter, the pressure sensor, the filter, the bleeder pump and the control system. Thereby, all the components will be located in the same space, making easier their manipulation.

The structure will be manufactured and built using a normalized profile, with dimensions of 20 mm x 20 mm and 2 mm, making the structure as light as possible. The CAD design is shown in Figure 7.15.

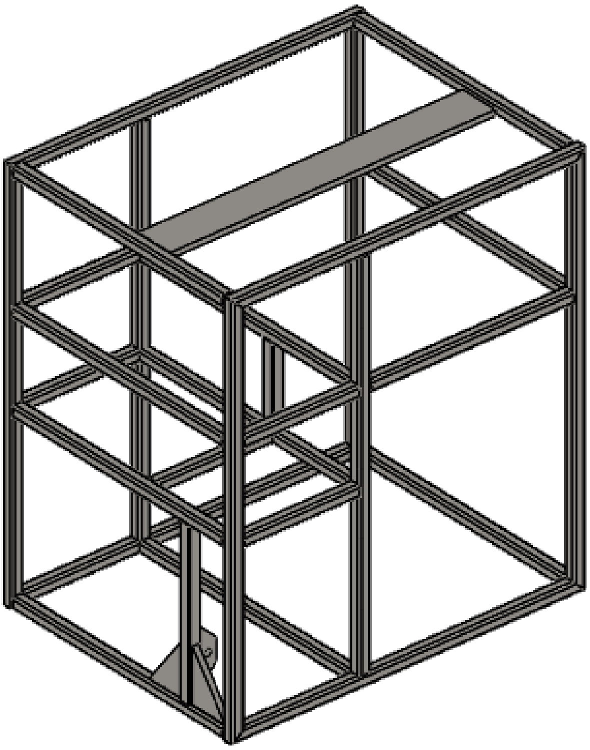


Figure 7.15 Structural design proposal

This design can be modified during manufacturing in the workshop, adapting in situ the distances more accurately in order to ensure that the support fits correctly and making more rigid the entire structure taking into account the different elements that will be installed on it.

In order to ensure the integrity of the structure during this life operation, some simulations have been performed to determine the maximum stresses and deformations. Performing these simulations, the structure could be analysed and different reinforcements will be added if it will be necessary. The studied areas have been the actuator junction and the master cylinder junction.

7.4.1. Structural simulation

As commented before, two simulations have been performed to ensure that the structure will support the operation loads. The worst-case areas are the master cylinder junction and the actuator junction, where the two pumps will be installed. The defined boundary conditions are the same for both simulations, fixing the base in the three degrees of freedom. The extra rigidity of the test bench and the plates has not been considered in order to obtain the worst case and have a safety factor. The boundary conditions and the studied areas are shown in Figure 7.16.

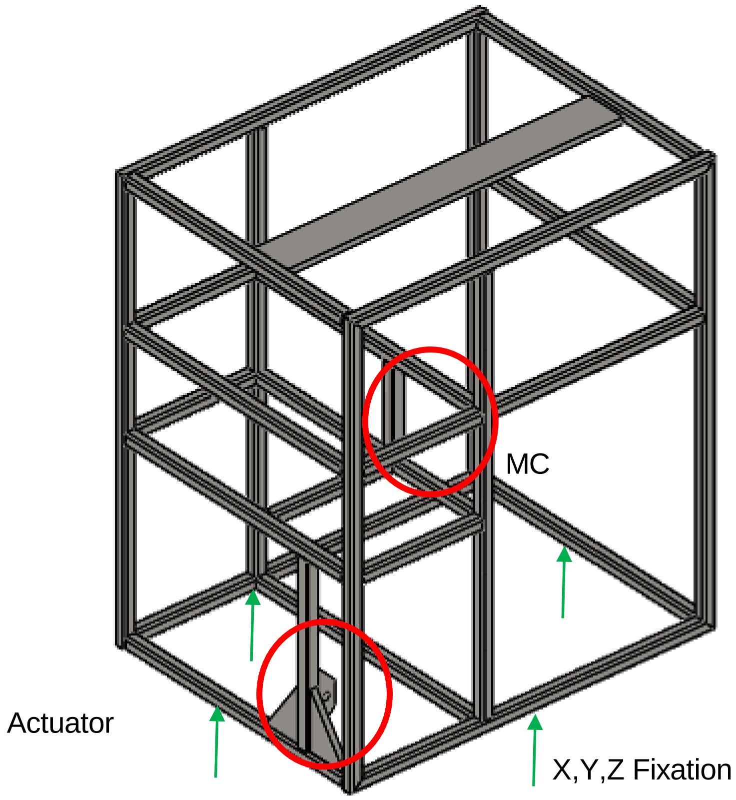


Figure 7.16 Structure - Boundary conditions and areas

The material used to simulate the structure is the 275J structural steel. The proprieties of this material are shown in Table 7.5 Structural steel propertiesTable 7.5.

UNE 00027-1	%C	%SI	%MN	Treatment	Yield Strenght (N/mm^2)
S275N	0,18	0,4	0,5	Normalized	275

Table 7.5 Structural steel properties

7.4.1.1. Actuator junction – Simulation

The applied load on the actuator junction is 2000 N, the maximum given by the actuator. The load is applied on the actuator junction, as shown in Figure 7.17:

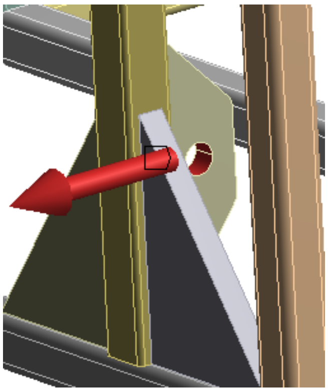


Figure 7.17 Load application – Actuator junction

The results that will be showed are the total deformation and the maximum equivalent stress (Von Mises). The results of maximum deformation are shown in Figure 7.18.

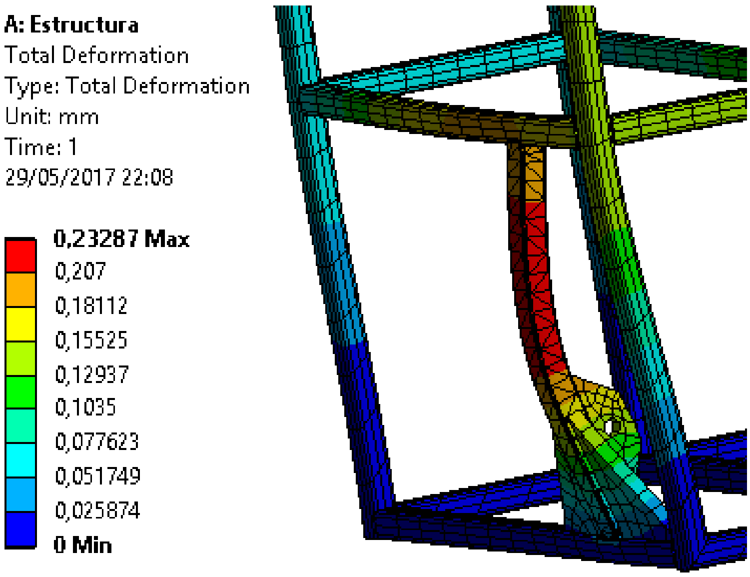


Figure 7.18 Maximum deformation - Actuator junction

The maximum deformation produced for this load is very low, having a maximum value of 0,23 mm in the middle of the structural profile of the studied area.

In the other hand, the results of the maximum equivalent stress is shown in Figure 7.19.

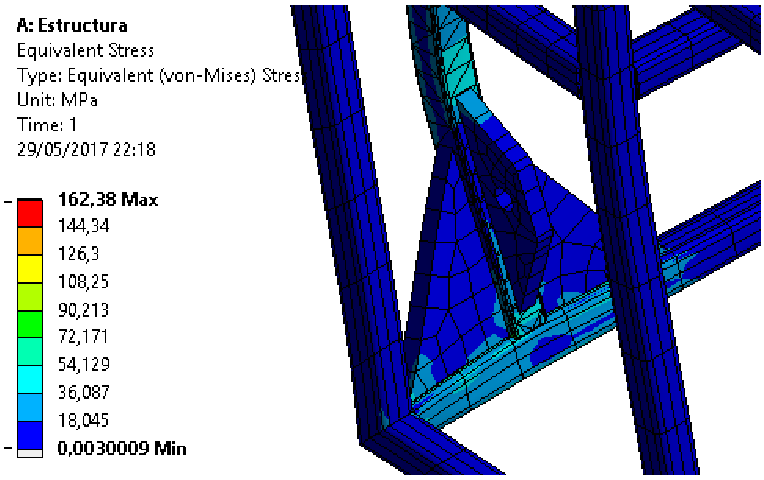


Figure 7.19 Equivalent Stress – Actuator junction

The maximum equivalent stress is located on the welded structure union, having a maximum value of 162,4 MPa. This value is far of the yield strength. For this reason, these area will not be modified with reinforcements and will be validate.

7.4.1.2. Master Cylinder junction – Simulations

In this case, this area will be more critical than the simulated before due to the high load that have to resist. The applied load in this case have a value of 6000 N, load that could be achieved when a 200 bar test will be performed. The areas where the load is applied are shown in Figure 7.20. The load is divided in two profiles (A and B), applying a distributing load of 3000N in each profile, simulating the fixation of the master cylinder plate.

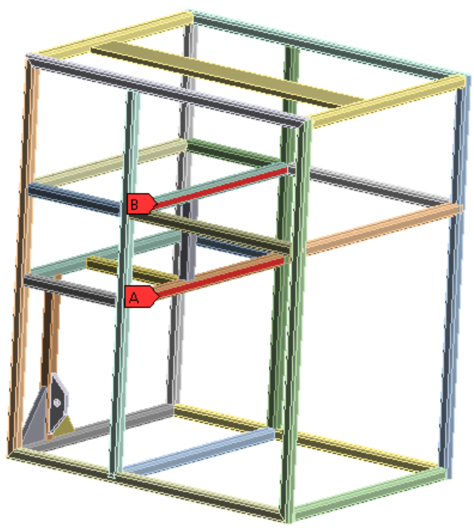


Figure 7.20 Load application - Master Cylinder junction

The total deformation result is shown in Figure 7.21.

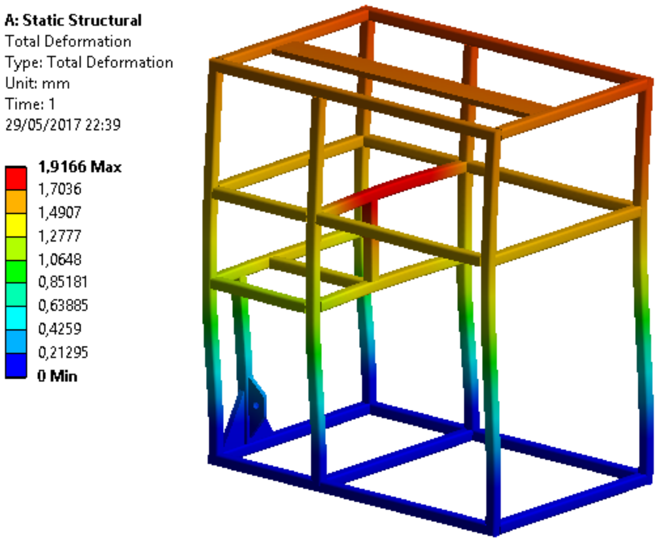


Figure 7.21 Total deformation - Master Cylinder Junction

The maximum deformation is in the middle of the structure (red area), with a maximum value of 2mm approximately. This value is acceptable taking into account that the different element as a plates and the workbench will give an extra rigidity on the structure. These extra components will be shown in section 7.4.2.

In the other hand, the result of the maximum equivalent stress are shown in Figure 7.22.

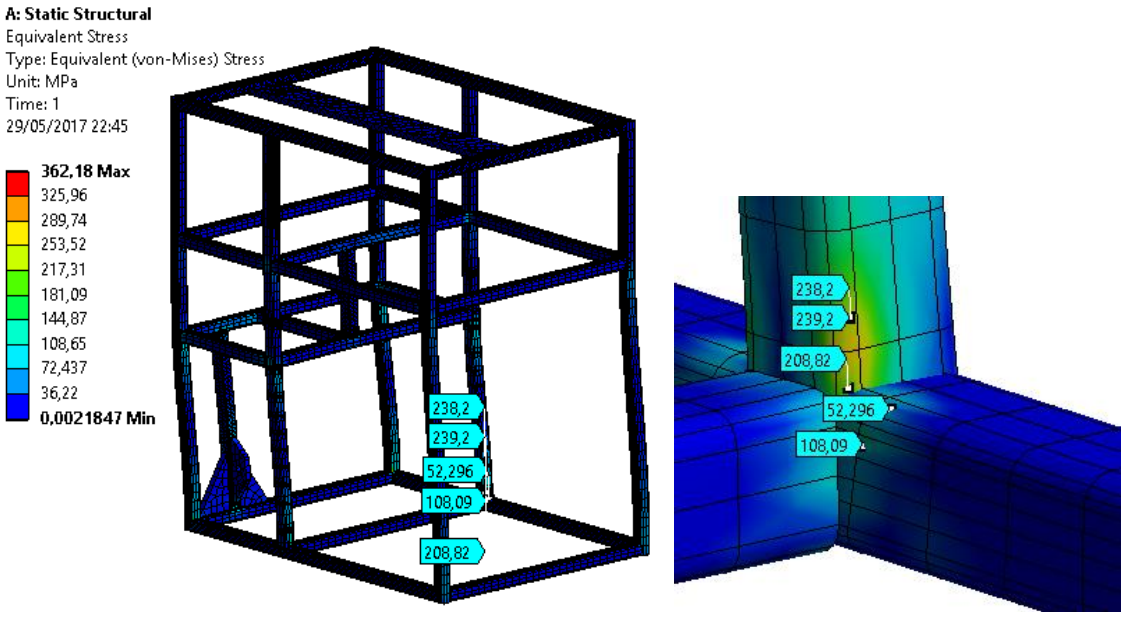


Figure 7.22 Maximum Equivalent Stress -Master cylinder Junction

The maximum stress is 240MPa, and is located on the welded structural junction. The value is acceptable, but some extra rib will be installed in order to reduce the stress in this area. The scale shows a highest value, but is due to a nodal error following the IDIADA simulation department criterion. The added ribs for increasing the stiffness are shown in Figure 7.23.

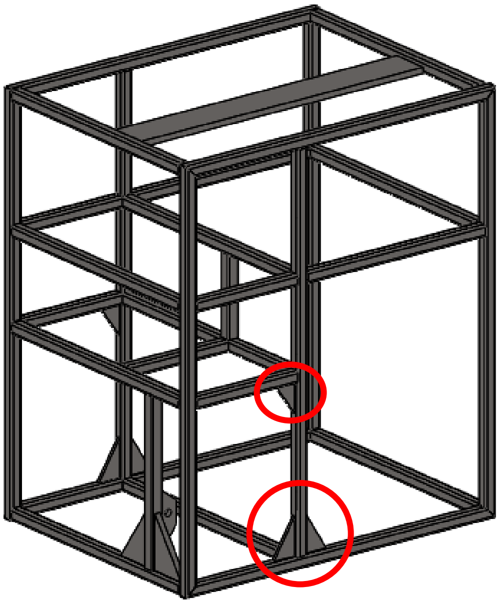


Figure 7.23 Structure - Ribs addition

The ribs have been installed in the areas where the stress is higher. A finite elements analysis has been performed to determine if these structure update improves the stress and deformation result. The results of deformation and equivalent stress are shown in Figure 7.24 and Figure 7.25 respectively.

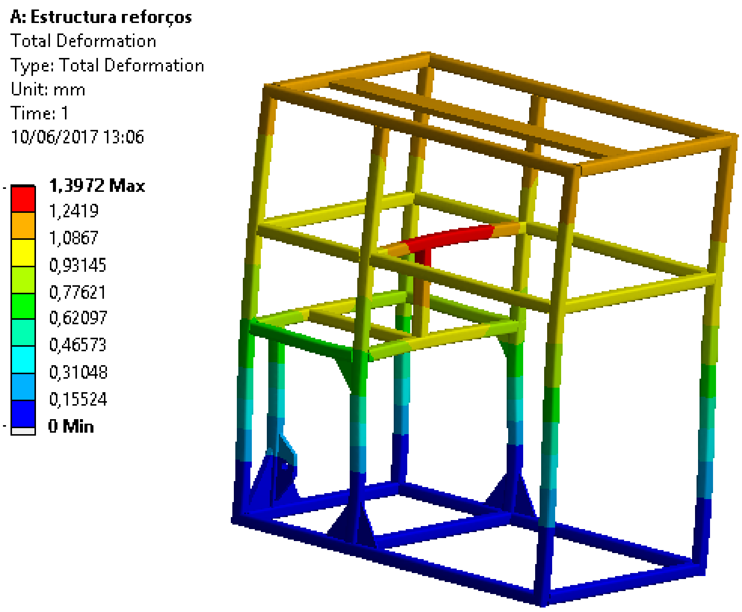


Figure 7.24 Total deformation - Structure with ribs

With the rib addition, the total deformation is improved, reducing the value from 1,9mm to 1,4mm.

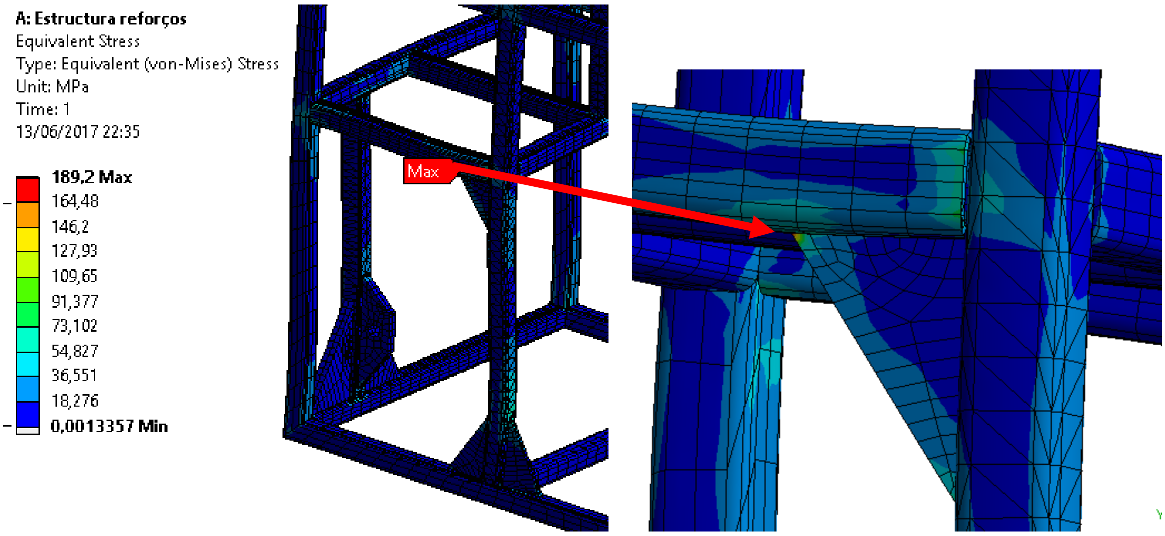


Figure 7.25 Equivalent stress - Structure with ribs

The equivalent stress of the structure is reduced considerably adding these ribs on the critical areas. The maximum value on the welded areas (considered the critical point), have a maximum value of 189 MPa, located on the corner rib. The area with the maximum stress is very small, and the structure with the rib addition is considered safer because no breakage and permanent deformation will be appear in operational conditions. In addition, the rest of the welded unions with the profiles have stress values between 110 and 60 MPa, values that are far from the material yield strength.

The ribs have a thickness of 5mm, and are the same material properties as the structural profiles.

In conclusion, the final structure will have the ribs in order to make safer and ensure this correct working during her life cycle. In addition, the maximum load will be achieved in few times. The detailed dimensions of the structure are shown and detailed in the attached drawings on annexes.

7.4.2. Structural assembly

After determining the stresses and deformations of the structure, being able to validate it, the components and parts that conforms the test bench could be distributed on the structure space.

The assembly of the structure and the lever, with the different parts explained in the chapters above, is shown in Figure 7.26. The lever and master cylinder position have been designed to respect the angle restriction, achieving the desired value of maximum pressure and fit all control components.

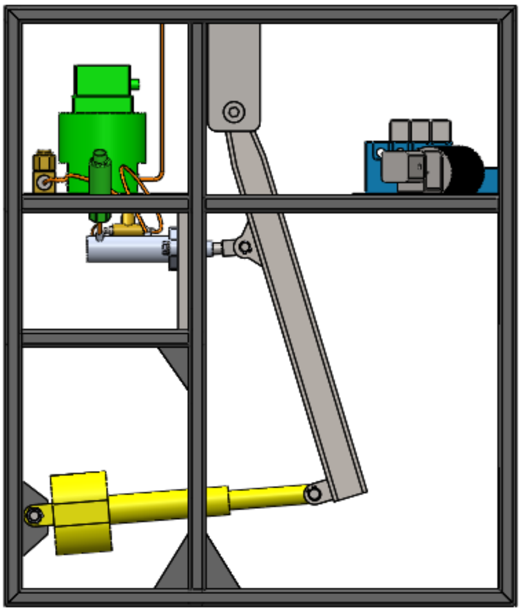


Figure 7.26 Structure assembly

As commented before, the actuator junction will be dimensioned to support the load reaction produced during the test realization. The thickness of the reinforcement ribs and the junction is of 9,5 mm, adding rigidity on this area. In addition, the rotational movement is allowed. A detail is shown in Figure 7.27.

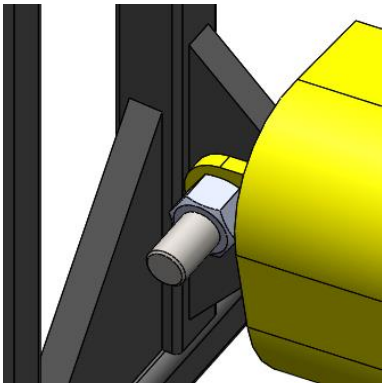


Figure 7.27 Actuator junction detail

Different plates will be installed on the structure to allow the different sensors and connections that forms the designed measurement system. In order to determine the space that will be need for the structure to allow the selected components, a CAD model of these assembly have been done, assembled, and distributed on the structure. The distribution of the elements is shown in Figure 7.28.

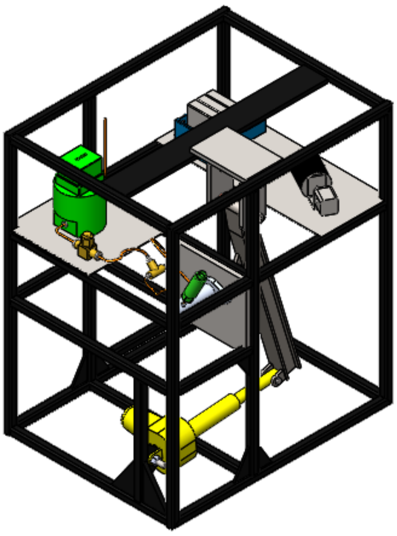


Figure 7.28 Sensors allowance and master cylinder subjection

The first plate contains all the measurement system, which is formed for the pressure sensor, the filter and the flowmeter. These elements have been located near the master cylinder in order to reduce the pipe longitude and simplify the piping circuit. The distribution is shown in Figure 7.29. The elements have been located upper the master cylinder to avoid the air apparition in the hydraulic circuit.

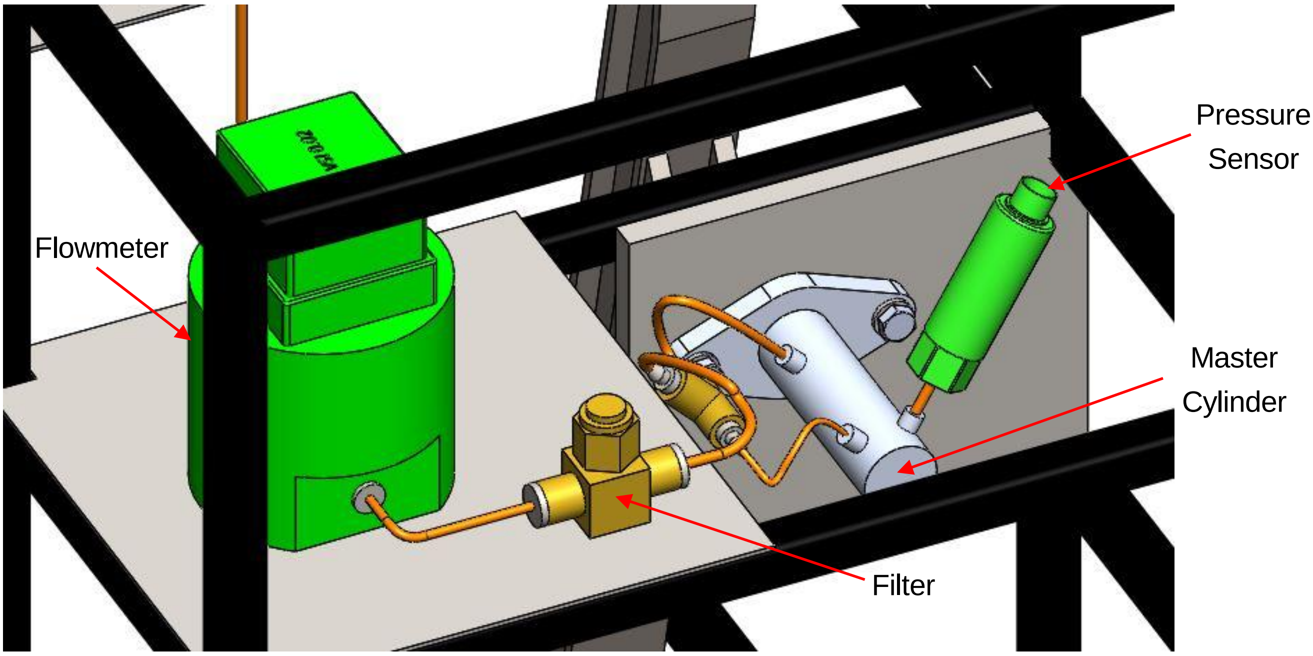


Figure 7.29 Structure - Distribution detail

The sensors distribution has been performed following a defined criterion. The pressure sensor has been mounted before the flowmeter because the pressure is a critical parameter to determine the fluid consumption. For this reason, the flowmeter will be assembled after the pressure sensor.

In order to determine that this assumption is correct, on the validation tests, a pressure sensor will be located after the flowmeter in order to determine the difference of pressure that supposes install the pressure sensor before or after the flowmeter.

In conclusion, the most important pressure, who affects the lecture of the flow, is the pressure immediately before the flowmeter device because is the system pressure.

In the other hand, an additional plate has been designed to allow the control module and the bleeder pump, to insulate and avoid the contact of the electrical devices with the hydraulic elements in case of fluid leakage. The distribution of these elements is shown in Figure 7.30.

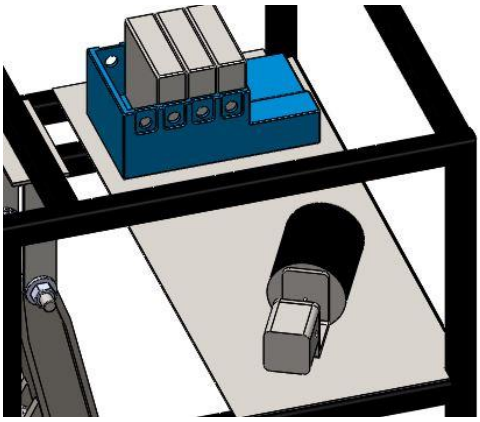


Figure 7.30 Structure - Control plate

In order to allow the lever movement, reduce the friction between materials and ensure the resistance of the loads transmitted by the lever, the implemented solution has been the installation of self-lubricating bushings. This solution have been chosen due to technical requirements because the technicians should have to perform different reparations or maintenance operations might disassemble the lever assembly. Implementing this design, the variable diameter of the screw avoids the flexion of the structural support plate, preventing the creation of an external load due to the screw fixation. Having this solution, the plat will contact the screw on the maximum diameter area, maintaining the position of the plate. The screw has been designed and mechanized, working as an axle and fixing the lever on the structure. Figure 7.31 shows in detail this design.

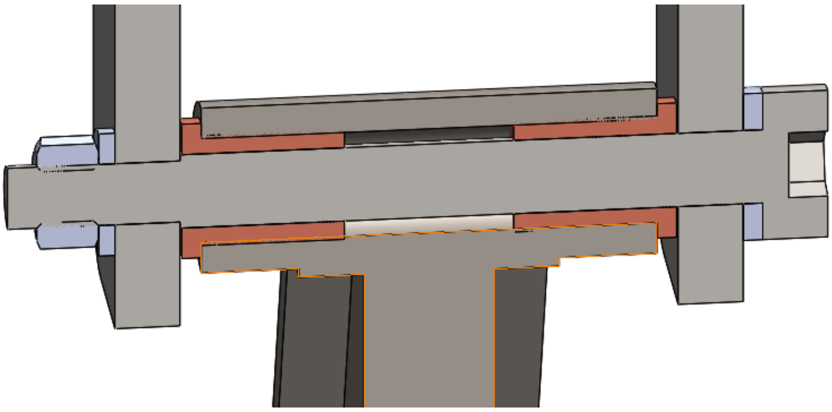


Figure 7.31 Lever junction scheme

The selected self-lubricating bushings has been calculated in order to ensure that the assembly will resist the reaction forces on the junction area. To calculate the specified part, the pressure on the area should be taken into account as well as the reaction force produced during the operation. Having these parameters and the axle external diameter, the minimum bushing length to support the load will be determined. The pressure and reactions values have been determined by simulation, using the ANSYS workbench software.

The data and assumptions to calculate and select the appropriate bushing are detailed in Table 7.6.

Parameter	Character	Function	Result
MIN^{-1}	M	-	23 min^{-1}
Axle diameter	Ø	-	12 mm
Distributed pressure	P	-	23 MPa
Reaction	R	ΣF=0	3300 N
Projected Surface	p	$p_f = \frac{R(kg)}{P\left(\frac{kg}{cm^2}\right)}$	1,43 cm^2
Lenght	L	$L = \frac{p(mm^2)}{\varnothing}$	12mm

Table 7.6 Bushing selection

The minimum length of the bushing must be 12mm. Consulting the data sheet from the AMES company, (provider) the selected bushing will have an external diameter of 17mm and a length of 25mm in order to have more surface inside the lever hole, providing a better subjection of this part.

7.5. Connection adapter

Different parts will be tested on the designed test rig; most probably, the connections will differ from component to component, or depending on the actual manufacturer. The most common thread sized diameter among hoses' connections are listed below:

- 10/125
- 10/100
- 12/100
- 10/150

In order to make easier the assembly of these components (specially the hoses) and ensure its compatibility with the designed test bench, a special component is designed with the most common thread dimensions. This element is shown in Figure 7.32.

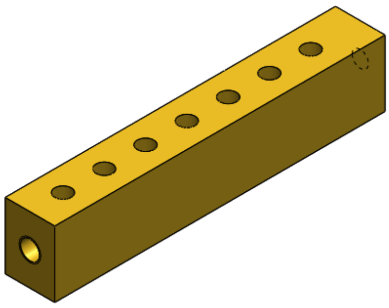


Figure 7.32 Hoses connection

The design has a hole that connects the circuit pipes, coming from the pressure sensor, and the bleeder pump aimed at purging the brake liquid. The hoses' connections have a cone to avoid the leakage of brake fluid. A cone on the bleeder pump side is also to avoid air entering inside the pipe. A scheme is shown in Figure 7.33. The dimensions are detailed in the drawings attached on the annexes.

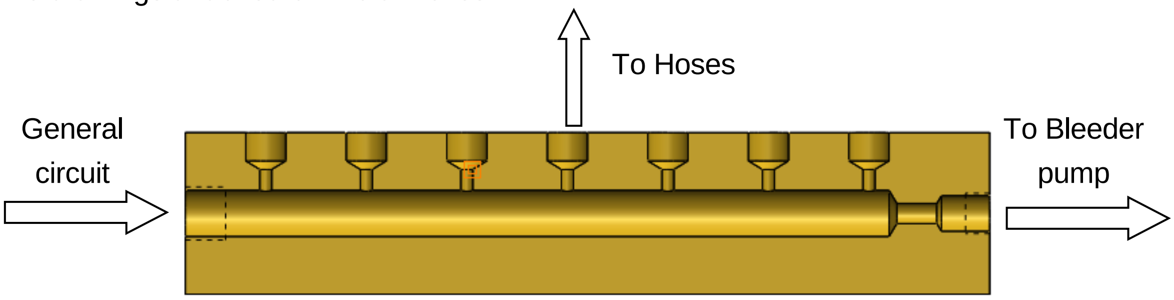


Figure 7.33 Hoses connection scheme

7.6. Test rig assembly

In this chapter, the general assembly of each part that forms the test rig will be showed and explained. The following renders will serve to understand the project and the distribution that have been thought to design the test bench. In the Figure 7.34 the design proposal for the test rig is shown.

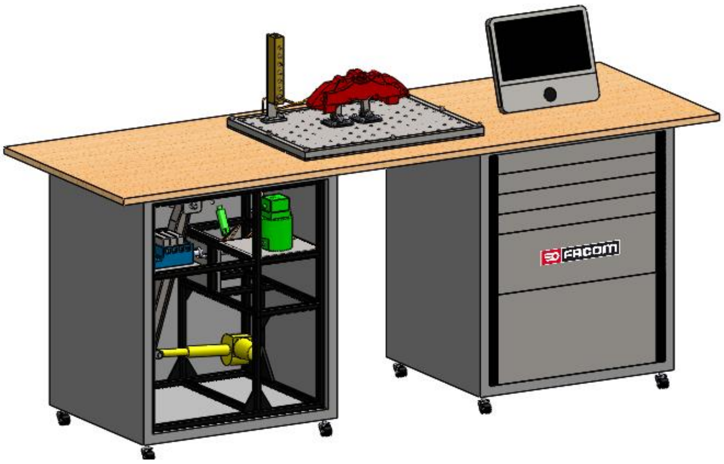


Figure 7.34 Test rig general assembly

As shown in Figure 7.34, the design has different parts that will be following commented. The first part is the structure allowance, where the workbench will be modified extracting the drawers and adapting the space to install the structure and the main components.

The second part that will be commented is the test area, formed by the base. The base has been fixed on the workbench surface to avoid the movement. On this base, the specimen that should be tested will be fixed to simulate the assembling on the vehicle. Furthermore, the connection adapter will be fixed on the base to connect the different hoses connection existing in the market. The test area is detailed in Figure 7.35.

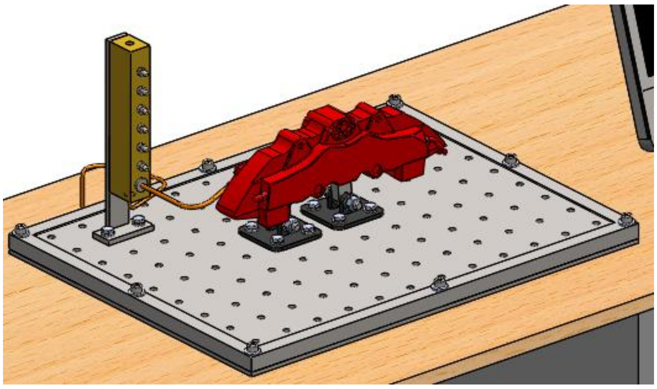


Figure 7.35 Test area detail

As shown in Figure 7.35, this area has different elements. A caliper have been assembled as example, in order to show how will be fixed these item on the base. The element that fixes the caliper on the test bench will be designed for each caliper type because the threated hole of the calipers is different depending on the dimension and manufacturer.

The test area is located on the middle of the test bench, and on his right, a computer has been set up to control the test. This computer is situated on this area because most of the technicians are right-handed and is more comfortable for them have the control unit on this side. Besides, the drawers under the computer will contain the different tools and components that will be used by the technicians to prepare and perform the test.
This area is shown in Figure 7.36.

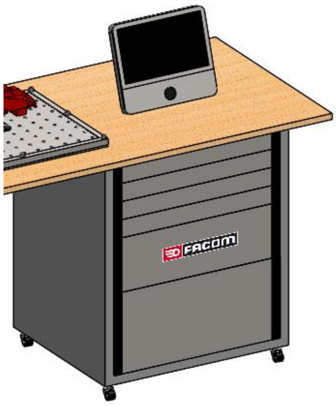


Figure 7.36 Computer and tooling area

On the top of the workbench, on the left side, the residual and the brake fluid tank have been assembled. Near the tanks, all the electrical elements will be installed. The electrical refrigeration (driver) and the power connection to the electric network will compose these elements.
On the other hand, a "window" will be created to allow the wiring and piping connection between the electrical parts and the hydraulic parts respectively. This window will be closed with a door in order to prevent the intrusion of elements during the test.
The parts in detail are shown in Figure 7.37.

Figure 7.37 Window and tanks

8. Software and Control

Software is designed by the braking systems IT department and the intern involved in the project to control the load of the actuator in function of the desired value of pressure. Besides, a data storage system is created in order to build a data base that will be useful to historically compare the different brake components that are tested.

The software is aimed to be user friendly and avoid problems. The objective of the software design is stablish a criterion to plot and save the results, having a template for having the same format in each test. The technician will have to input the data to perform the test depending on the specimen. The designed software has three screens to input the data test and one to see “in situ” the test results. These screens are listed below:

- Main Menu
- Settings
- Test Information
- Test Execution

The main menu has been set to be the principal window, where the user can set up the test specification. These specifications can be introduced on the configuration window, which includes the settings (Figure 8.2) and the channels options. However, the main menu includes the configuration files, where the user can save the test and open previous tests performed with the test bench.

The last step is starting the test. Previously, the settings and the channels must be defined. The main menu screen is shown in Figure 8.1.

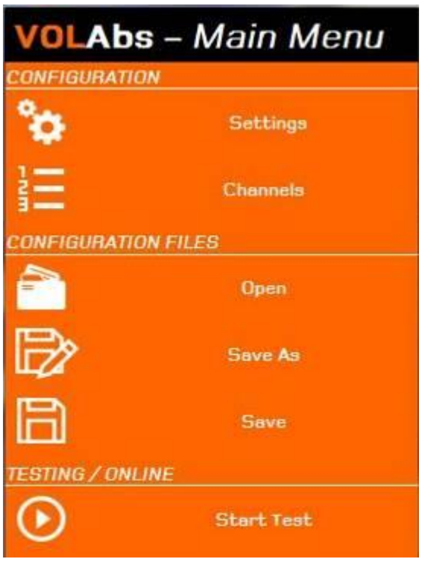


Figure 8.1 Main menu

As explained before, the settings must be defined before to perform the test. On the settings screen, the user has to introduce different parameters in order to set up the test. The data introduction is divided in four configurations. The first one is the pressure profile configuration, which is listed below:

- Number of steps→ Different pressures that will be achieved on the hydraulic circuit. These steps are shown in graph from Figure 8.2.
- Pressure Increment → The increment of pressure must be defined in relation with the number of steps and depending on the desired pressure value.
- Global Slew Rate → Is the gradient of the straight, which will be the same in each step.
- Global Section Duration → Is the time where the pressure will be constant, and is the same for each step.

On the other hand, the controller configuration will be used to select the channel that will control the steps. Clicking the drop-down on the feedback channel, the sensors of pressure or volume could be selected. Besides, on the data logging configuration, in the log gate the register frequency has to be introduced. Normally, this value will be 100 Hz.

Finally, the last step is define the channels of interest. In this case, will be the pressure (pressure sensor), the volume (volume sensor) and the bleeding (bleeding pump). An example of settings configuration is shown in Figure 8.2.

Figure 8.2 Settings

After configuring the settings, the next step is the test execution. Before the execution, some parameters must be defined on the test execution screen:

- Project information: The project code (department internal number) and the test description will be mandatory. Furthermore, in order to classify the project and the report, the vehicle manufacturer and the vehicle model might be introduced.

- Test parts: In this case, the test component must be selected. For the calipers, the wheel position, the type (floating/fixed), number of pistons per side and the diameter has to be specified. The component manufacturer and their specifications is optional.

In Figure 8.3, an example of the data introduction before the test execution is shown.

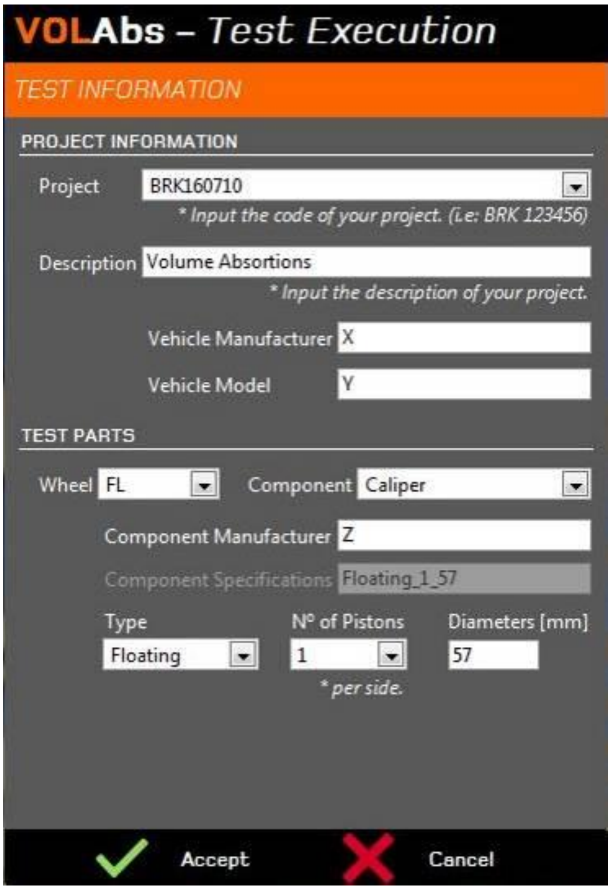


Figure 8.3 Test execution input data

After the data introduction, the user will be ready to start the test. When the user will press the *start* icon, the software will start to run and a process bar and light will advert that the test is in process. During the execution, the results in each step will be numerically and graphically showed on time to evaluate the results during the test execution. If somethings goes wrong, a stop function is set up to suppress the test and modify parameters. The test execution results screen is shown in Figure 8.4.

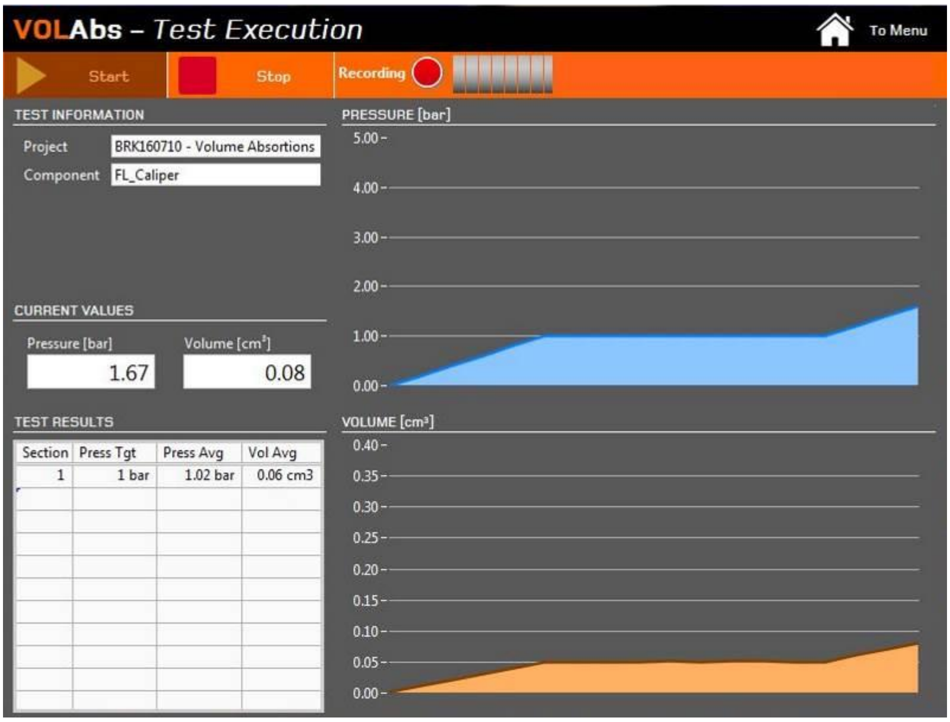


Figure 8.4 Test execution results

When the test will be done and another test configuration will be set up on the bench, the circuit needs to be bled to remove the existing air on the system. When the bleeder pump is working, an advertisement will appear on the screen advising to the user that the bleeder pump be activated.

Finally, a security channel has been set up. The input data will be the position of the master cylinder (using a position sensor). The test will be stopped when the master cylinder will be moving and the pressure stays stable or decreases. Thereby, stopping the linear actuator different problems will be avoid, in example the end stroke of the master cylinder, who can broke the pump and the linear actuator.

9. Manufacturing

The manufacturing process is conducted at Applus+IDIADA Brakes department's workshop. The process is to be divided into different steps:

- Workbench manufacturing
- Structure manufacturing
- Test rig assembly

9.1. Workbench manufacturing

The workbench is fitted with wheels as it is thought to be mobile, so (if necessary) the measurements can be conducted under the vehicle or nearby. In addition, one of the drawers is removed to have extra space for the structure and all the different components it houses. In addition, the space left by the drawer is altered to install the electrical part of the control that must be ventilated to avoid the overheating of the control system. Some figures of this process are shown hereunder:

Figure 9.1 Workbench manufacturing

Before the plates and structure installation, other operations have been made on the test bench, where some modifications have been performed in order to make easier the installation of the electrical and hydraulic components. Figure 9.2 shows the electrical installation, the tanks and the window to have access inside the system

Figure 9.2 Workbench modifications

Another step of this process is the installation of the plates. These have been machined, based on our design, by an external supplier. Figure 9.3 show the assembly of the plates on the test bench following the 3D CAD render showed before. The plates have been fixed on the bench in order to avoid their movement.

Figure 9.3 Upper plate and lower plate

Finally, the last part that will be shown in this section is the connection adapter. Figure 9.4 shows the adapter with different types of connection. With this solution and as explained before, the different types of threat dimension can be connected to perform the test with an universal connection, making easier the work of the technicians and reducing the test time.

Figure 9.4 Connection adapter manufacturing

9.2. Structure

The structure is the most important element. This part has to support the applied forces and the weight of the selected elements to perform the tests. This structure must be rigid, and have been manufactured based on the CAD design. However, different modifications have been performed during the manufacturing in order to make simple the design and reduce the total weight of the assembly.

As explained before, the structure will allow the major part of the selected elements. Some of them have been designed and manufactured (lever and MC junction). The lever has also been mechanized externally by a supplier, respecting our design. The lever has been manufactured without welded parts, achieving a high rigidity and maintaining the designed measurement of the part. In the other hand, the final price has been increased due to this decision. Figure 9.5 shows the manufactured lever and the main important areas, where the actuator and the master cylinder are to be fixed.

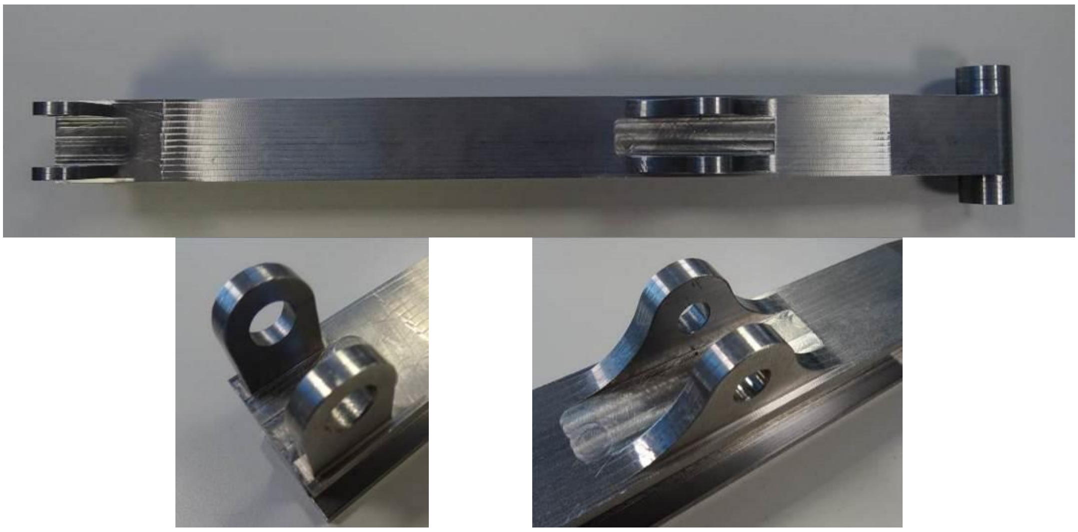


Figure 9.5 Lever manufactured

To transmit the load from the actuator to the master cylinder, a specific junction has been manufactured with the shape of the master cylinder, copying the real master cylinder push rod. The part should have the same dimensions that the master cylinder hole in order to have the distribution of force without deviation. Figure 9.6 shows the manufactured part.

Figure 9.6 Master cylinder push-rod

Taking into account the commented parts, the structure has been manufactured using 20x20 steel profiles. In order to build the structure, the first step was the construction of the contour. Then, the lever and actuator position have been defined to install the parts on the correct position. Finally, and considering the position of the lever and the actuator, the master cylinder has been assembled on the right position. In addition, and taking into account the position of the actuation system, the plates to support the sensors and the software control have been welded on the structure.

Before to assembly the rest of the components (sensors and entire hydraulic circuit) a previous test has been performed to ensure that the pressure of 200bar without damaging the structure. The test is performed moving the lever until the 200bar, which will be showed in situ by a manometer. Figure 9.7 shows the previous test configuration.

Figure 9.7 Structure verification

After the structure verification test, an issue has been found on the master cylinder. When the desired pressure is achieved and has to be hold during a defined time, the pressure value decreases to zero. No leakage has observed on the tubing and the manometer. The issue is detected on the master cylinder, where the internal junctions are broken and returns the brake liquid to the tank when the pressure has to be held. This breakage of the master cylinder can indicate that maybe the pressure target can not be achieved because the commercial parts can not support this value.

On the other hand, in order to verify the structure resistance, a higher pressure has been applied. In order to make safer the structure, the designed ribs will be installed on the structure.

The final step for completing structure is painting the structure and assembly all the components on it. Figure 9.8 shows the distribution of the different elements that forms the data acquisition and the control system.

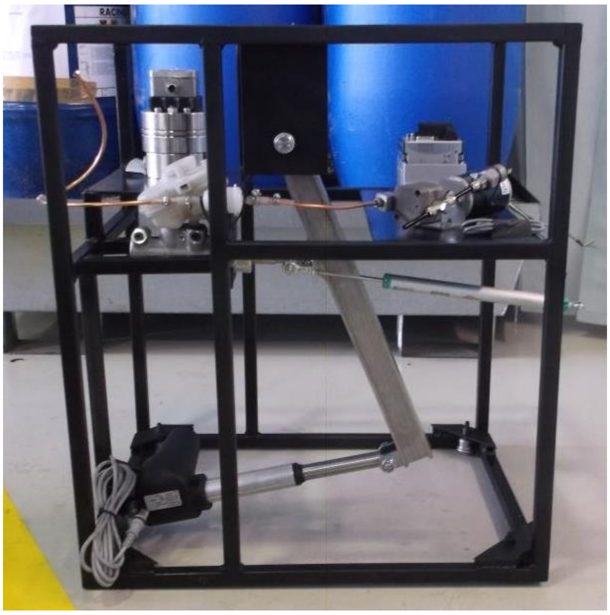
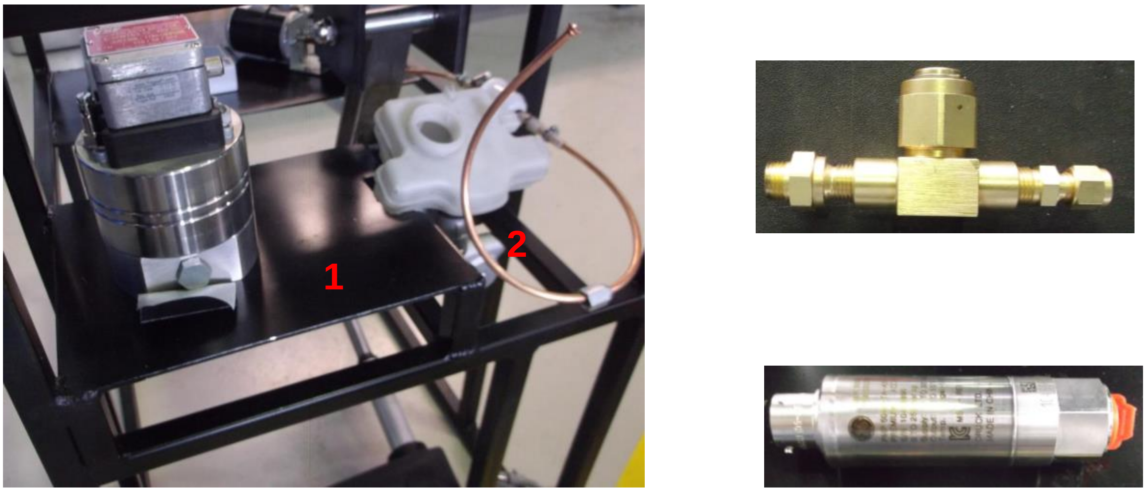


Figure 9.8 Distribution of the elements – general view

In Figure 9.9 is shown in more detail the master cylinder, the flowmeter, the pressure sensor and the filter. Note that the filter will be located between the master cylinder and the flowmeter. In addition, the pressure sensor will be connected at the second chamber of the master cylinder, following the design showed in Figure 7.29.



2- Filter

1- Pressu
senso

Figure 9.9 Sensorical distribution

The number showed in the right image references the single images. The pressure sensor and the filter has not showed in the image because the test rig is not finished when the intern lefts IDIADA.

In the other hand, the position of the lever assembly is shown in more detail in Figure 9.10. The figure shows the junction of the lever with the master cylinder and the position of the transducer.

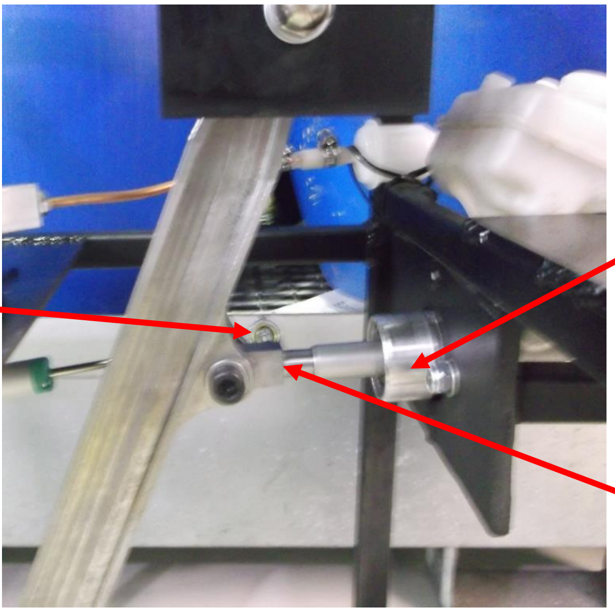


Figure 9.10 Sensorial and lever assembly

10. Validation

10.1. Previous work

A previous work has been done to understand the actual fluid consumption of different braking parts. To do so, results measured historically by Applus+IDIADA (using both methods explained in section 5.2) have been gathered. Absorption (volume) values are represented against the piston diameter of the caliper. Whenever a caliper has more than a piston, the equivalent area of all pistons is calculated. On the other hand, absorption (volume) values are represented against the hose length.

10.1.1. Caliper fluid consumption

In this chapter the resume of previous test to measure the fluid consumption for the calipers will be shown. To compare the different values of fluid consumption, different caliper configuration will be taken and compared. In some cases, for example, for a three cylinder caliper, the effectiveness area will be determined to include this calliper cylinder dimension in a determined category.

The amounts of samples that have been considered to carry out the comparison are detailed in Table 10.1.

Cylinder diameter	Nº of samples
60 mm	5
57 mm	4
54 mm	4
51 mm	2
43 mm	3
38 mm	4
36 mm	2
34 mm	3

Table 10.1 Number of samples – Front calipers

In order to compare the fluid consumption value for the different caliper configuration, a graph has been done to observe the differences between calipers. The comparison results are shown in Figure 10.1.

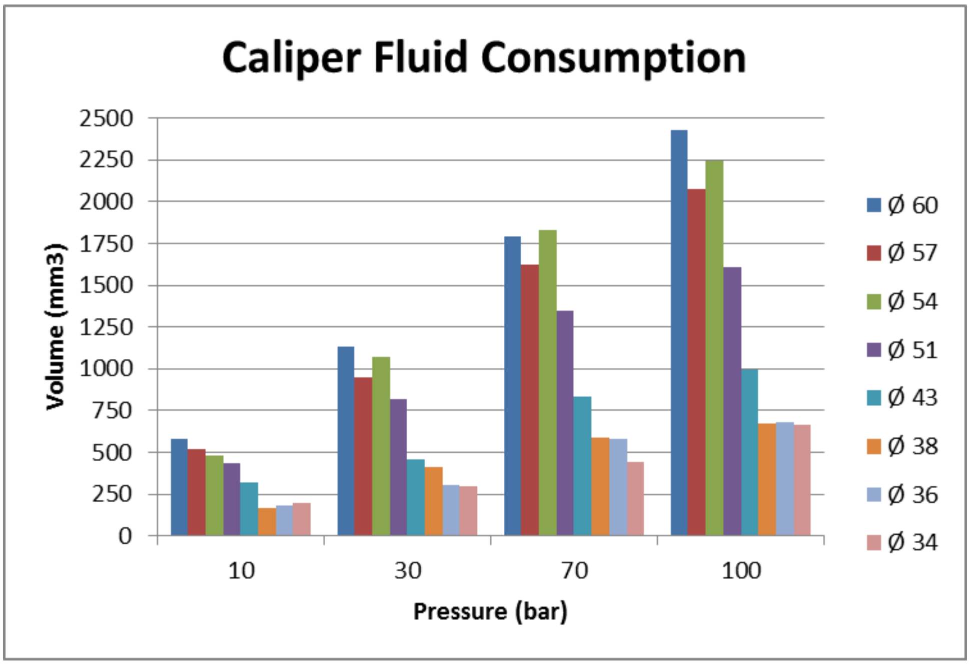


Figure 10.1 Caliper fluid consumption

As shown in Figure 10.1, the results have non-linearity, having similar values between configurations and the smaller calipers have a higher value of fluid consumption than a bigger caliper. This non-linearity might be due to different reasons:

1. Measurement method:

    - Test repeatability → High human factor
    - Data acquisition → Some values extracted from graphs have been estimated to make the comparison.

2. Previously, has been commented that the bigger caliper has to have the bigger fluid consumption value, and this assumption may not be true. Having a different brand and model caliper, with the same dimensions, the absorption value can be different:

    - Material compressibility and wear of friction can be different.
    - Caliper deflection and deformation can be different → Design, material mechanical behavior, etc.

3. Having a big number of samples, and making a caliper comparison of different caliper dimension (40 mm versus 50 mm), the difference of the fluid consumption value must be observed.

In order to establish a criterion to verify the results obtained on the test bench, a polynomic tendency line has been calculated based on the results that are shown in Figure 10.2. In this case, some values have been modified to follow the desired tendency and obtain an approach result.

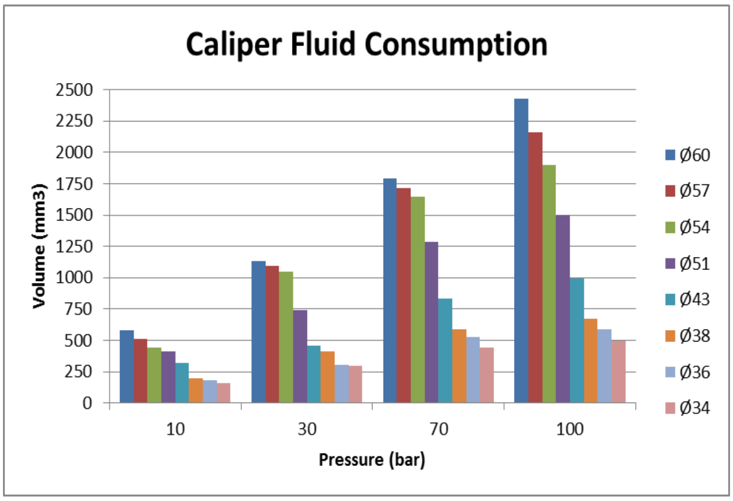


Figure 10.2 Caliper fluid consumption modified

As shown in Figure 10.2, the results follows a "linearity", that is what we expect when the comparison starts. The objective of this comparison is to obtain a general equation that gives an approximate volume before the test taking into account the caliper diameter and the application pressure. In the following graphs, the different equations are shown in Figure 10.3 in function of the different pressure steps.

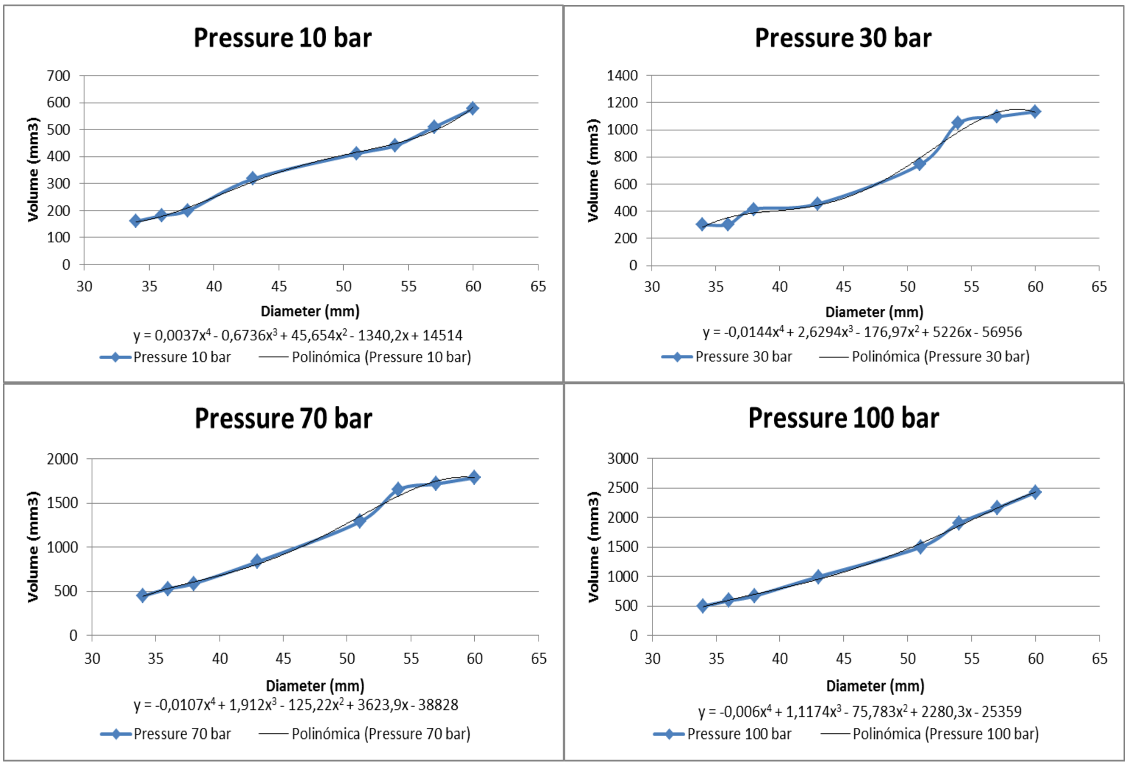


Figure 10.3 Regression lines for each pressure value

The obtained equations for each pressure value are shown hereunder:

- **10 bar →** $y = 0,0037x^4 - 0,6736x^3 + 45,654x^2 - 1340,2x + 14514$
- **30 bar →** $y = -0,0144x^4 + 2,629x^3 - 176,97x^2 + 5226x - 56956$
- **70 bar →** $y = -0,0107x^4 + 1,912x^3 - 125,22x^2 + 3623,9x - 38828$
- **100 bar →** $y = -0,006x^4 + 1,1174x^3 - 75,783x^2 + 2280,3x - 25359$

Where:

- "*y*" is the volume in mm^3
- "*x*" is the pressure in bar

Previous functions will provide an approximate value of absorption before the test performance depending on the pressure value. A general equation – involving the four equations – has been determined to predict the absorption value before the test, involving the pressure and the caliper diameter. This equation is shown hereunder:

$$volume = 45,6 diameter + 11,5 pressure - 1828$$

The equation showed before, has been obtained using *Minitab*. This software allows obtaining a multiple linear regression using three variables. The 3D graph that shows the three variables is shown in Figure 10.4.

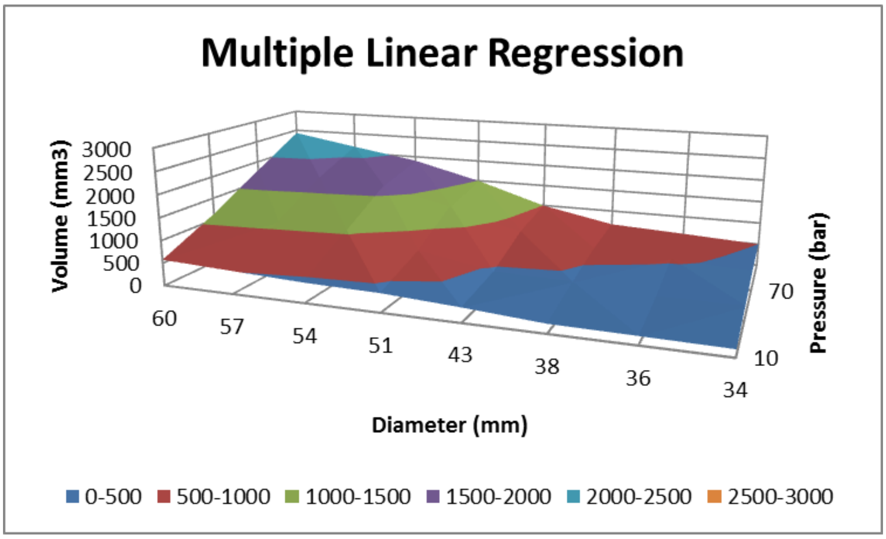


Figure 10.4 3D graph - Multiple Linear Regression

Using the expression obtained by the multiple linear regression analysis, the values that will be obtained on low and high pressures will vary from the reference. This is for different reasons:

- When a low pressure is applied (10 bar), the braking system does not compress all the brake fluid, having various fluctuations on the final measurement.
- On the other hand, when a high pressure is applied (100 bar), different parameters are appearing on the system due to spring compression, pad compression and different mechanical elements that conform the braking system.
- Finally, having a linear equation, the values will not adjust to the real/previous volume results. The best option would have been the calculation of the equation using a polynomial function.

For this reason, the volume values that will be calculated using the multiple linear regressions will be when a 30-70 bar pressure will be applied. In this situation, the fluid is more stable, without fluctuations and the rest of components that take part of the braking system does not have several deformations (i.e. pad compression →deformation).

10.1.2. Hoses fluid consumption

The fluid consumption on the hoses has been compared between the obtained values from the previous tests performed at IDIADA and the SAE – Society of Automotive Engineers - reference paper (Antanaitis, Riefe, & Sanford, 2010) **[1]**. The comparison is shown in Figure 10.5.

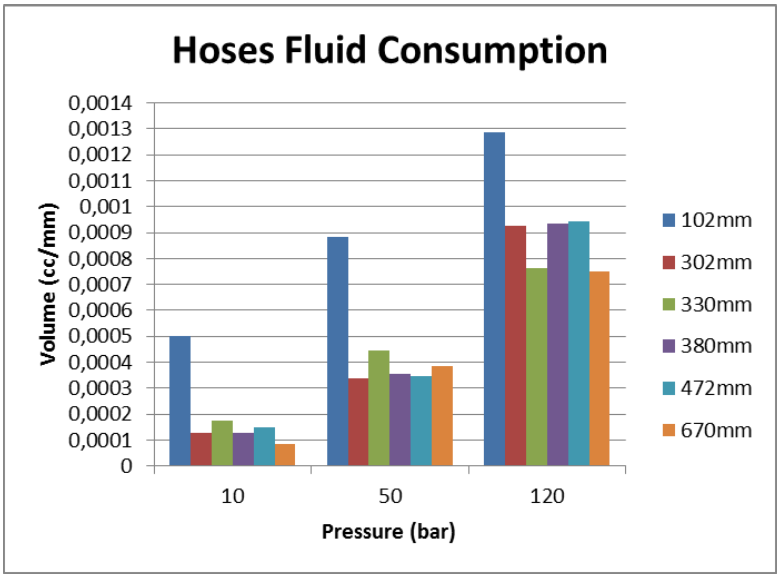


Figure 10.5 Hoses fluid consumption comparison

In this case, the hoses longitude used to compare the values obtained in the tests performed at IDIADA are listed below:

- 302 mm
- 380 mm
- 472 mm

The reason for using these hose dimensions is that in the previous test the hose dimension is not specified.

The difference of fluid consumption in the different hoses' is due to material differences and reinforcements of this part. For this reason, the material should be taken into account; due to a reinforced hose will have a minor fluid consumption. In this comparison the material has not been taken into account due to lack of information.

The reference will be the SAE paper (Antanaitis, Riefe, & Sanford, 2010), where there is an extensive list with different hoses measure and the corresponding value of fluid consumption when different pressure values are applied. For this reason, the criterion to compare the hoses and validate the absorption results will be the cc/mm, comparing the absorption with the length.

10.1.3. Pipes fluid consumption

The results of the pipes will not be compared with any previous result due to the difficult to obtain the total length of the piping. For this reason, the comparison of this braking system part is disesteemed.

11. Planning and budget

11.1. Planning

As an *ideada express,* the planning was defined by Innovation department. In this case, different tasks and timings have been defined to achieve the goal. The planning has been defined considering full time dedication by the intern since September. In this case, the intern only has been full time since February, and the project currently is not on time. Also, during the last two months (February and March), the project has been in standby due to unavailability of department technicians, causing a delay on the timing and impeding the achieving of the objective.

Nombre de tarea	Duración	Comienzo	Fin
State of the art	15 días	lun 19/09/16	vie 07/10/16
Rig design	55 días	lun 10/10/16	vie 23/12/16
Material selection	15 días	lun 05/12/16	vie 23/12/16
Software development	35 días	lun 26/12/16	vie 10/02/17
Rig manufacturing	40 días	lun 16/01/17	vie 10/03/17
Validation	16 días	lun 13/03/17	lun 03/04/17

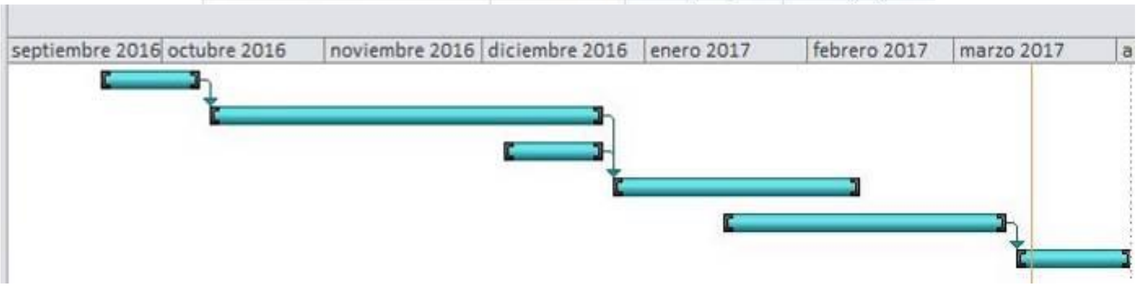


Figure 11.1 Gant diagram

The tasks have been distributed taking into account the following ranges:

- Internship: Main engineering duties will be covered through IDIADA's University Program, where these activities are meant to last 750h.
- Senior and Software Engineer: The intern will be supervised by a senior engineer from the Brakes department, as well as receiving support from a software engineer to develop the project.
- Technician: The technician will manufacture the test bench according to the engineering specifications.

The Innovation department has planned three milestones to achieve the objectives of the project. In addition, the employees to take part in the different phases of the project have been initially defined. The milestones and the task distribution in each milestone are shown in Table 11.1.

Task	Milestone	Employees	Comments
Investigation	31/10/16	Intern	On time
		Senior Engineer	
Design and Manufacturing	31/01/17	Intern	The design and different machined parts are on time. The bench is not finished.
		Senior Engineer	
		Technician	
Validation	31/03/17	Intern	Some issues had occurred and the validation is postponed. The bench is not finished.
		Senior Engineer	
		Technician	

Table 11.1 Task distribution and milestones

As explained before, the project is not on time due to the following reasons:

- Material selection: During the design and manufacturing task, different problems to select the appropriate material have been found, in special with the flowmeter. Was very difficult to select this device because in our application, the flow is very low and most of these devices are not designed for the designed application.

- Design: Problems on the lever design have occurred. The lever must be rigid and light, to reduce the final weight. Different proposals and CAE studies have been performed and it has taken several days of studies. In addition, the external company has delayed the machining of this part, fail to fulfill on the estimated timing.

- Manufacturing: The manufacturing process has been delayed due to the design and material selection delays. In addition, due to department priorities, the manufacturing has been stopped for several weeks. This stop has affected on the timing and has impeded the realization of the test rig validation.

On the other hand, the non-prevision of holidays, the exams week and the department previsions have been affected the development of the project.

11.2. Budget

The budget takes into account the bought material and the employee tasks. As an *ideada express* project, the maximum budget to buy the needed material is 10.040.00 €, limited by the Innovation Department. Nevertheless, this limit has been reached due to different issues during the project development. The detailed budget is shown in the following tables.

Sensors

Component	Cost (€)
Flowmeter	3899
Pressure	636,38
Filter	75,05
Calibration	569
TOTAL	**5179,43**

Table 11.2 Budget - Sensors

Machining

Part	Cost (€)
Sub plate	1090,95
Plate	430,80
Lever	424,60
Push-rod	275,30
Connection adapter	315,20
TOTAL	**2536,85**

Table 11.3 Budget - Machined parts

Control

Part	Cost (€)
Driver	139,66
NI module	2992,02
TOTAL	**3131,68**

Table 11.4 Budget – Control

Components

Component	Cost (€)
Master Cylinder	85,9
Actuator	528,51
Bleeder pump	202,25
Workbench	1738,31
Tooling	40
TOTAL	**2594,97**

Table 11.5 Budget – Components

As commented before, some issues have been occurred during the project, as example is the mistake on the connection adapter design and the rupture of the master cylinder during the previous tests. This parts have been replaced and have incremented the cost of the project.

Issues

Issued Part	Cost (€)
Master Cylinder	85,9
Connection adapter_V2	330,25
TOTAL	**416,15**

Table 11.6 Budget - Issues cost

As a resume, the final material budget is shown in Table 11.7. In addition, the engineering cost will be considered in order to obtain the final budget.

Part	Cost (€)
Sensors	5179,43
Machining	2536,86
Control	3131,68
Components	2594,97
Issues	416,15
Engineering	6050
TOTAL	**19909,09**

Table 11.7 Budget – Final budget

The final budget is acceptable considering that the rig can be sold to any OEM. In addition, the amortization of the test rig is fast because the price of the tests are expensive. Finally, an estimation made by Applus+IDIADA marketing department, have estimated that the amortization of the test rig will be real after one year of this operating start.

12. Conclusions

The opportunity to develop the final master thesis in a reference company as IDIADA has been a great experience and a grateful opportunity because the project was ambitious and the professional experience was a plus to develop my future career.

The test rig to measure the volumetric absorption of the different braking system components' showed in this document is an innovation in the automotive field. As explained before, some specific test benches are currently working only for specific measurements (i.e. Hoses). In this case, the designed test bench offers to the customer the possibility to test different parts of the braking system components' in the same bench, reducing the testing time. In addition, the designed test bench is mobile, providing flexibility to the test technicians and avoiding the collapse of the workshop.

The pressure target to achieve by the system must be 200 bar. This pressure in driving conditions will never be achieved and only will be achieved in specific tests. However, the test bench is over dimensioned because different elements do not support this pressure. An example is the master cylinder, which plastic junctions broken when the maximum pressure is applied. This target has affected the entire project, having to design a rigid lever and a structure that must resist all the assembly as well as select the appropriate sensors to ensure the lecture at the highest pressure.

The flow meter and pressure sensor are one of the most important parts in the test bench. The flow meter has been over dimensioned due to the reasons explained before in this section, having serious problems for founding the correct sensor and having to build a structure prototype to make previous tests and select the correct flow meter. The selected flow meter is over dimensioned because the flow is very low in relation to the highest pressure that they have to support. Having a lowest target pressure, this step would have been easier and we would have waste less time due to the provider offered flow meters with less pressure resistance that complied the requirements of precision and minimum flow rate.

On the other hand, the lever and the structure have been dimensioned in function of the maximum pressure target. The conclusion is the same as commented before, if the pressure would have been lower (130 bar approximately), the design would have been smaller and cheaper than the designed one. However, the designed lever and structure, as well as other designed parts, accomplishes the target of load resistance and does not have an excessive displacement.

In conclusion, if the customer requirements would not have been described to achieve a pressure target of 200 bar, the test bench would have been more simple and cheaper.

The specific software thought and designed for this test bench has caused an inflection point on the software of the different benches in process of building at the braking systems department. The software is user-friendly, and is designed to be understood by everybody and for having a data base of the all performed tests. Thus, the different tested parts will be saved in the correct folder depending on the test and in a future, the engineers can perform some estimations and studies about the fluid consumption and will have all the test correctly classified. Finally, as is the software designed, is impossible to make a mistake because the test will not start until all the required data for the classification is completed. For this reason, is a great innovation for the braking systems department.

The tests have not been performed by the intern due to the decision of him to left IDIADA for starting new professional projects. For this reason, a validation has been done to correlate the performed test in the test rig and the previous tests performed with the current methods. The results have not been showed due to confidential information. However, the comparison performed to validate the tests before starting to test on the rig and the performed tests on the manufactured test rig have similar values. For this reason, we can confirm that the design, the equipment selection and the software is correct and have been designed and thought successfully. Furthermore, we can confirm that this test rig will be useful in order to determine the master cylinder dimension and ensure the best pedal feeling for the customer in driving conditions. The test rig will be useful to investigate the absorption of each braking system part and increase the development of the pedal feeling.

Once the correct working of the test rig is confirmed, we can conclude the benefits to offer this service by IDIADA braking systems department. The benefits are listed below:

- Add value for IDIADA, bespoke equipment to measure the volumetric absorption of the brake system is not common within most OEM’s, as they tend to rely on the design figures given by the supplier of the component in question. With this bench, the OEM’s can test their own designs and take decisions faster.

- Benchmarking activities: accurate volumetric figures are desirable to target a certain pedal feel and size a new braking system.

- Product development activities: faster and reliable measurement to help solving possible issues such as mediocre pedal feel or a mistaken master cylinder sizing.

13. References

[1] Antanaitis, D., Riefe, M., & Sanford, J. (2010). *Automotive Brake Hose Fluid Consumption Characteristics and Its Effects on Brake System Pedal Feel.* SAE International.

[2] Hon Pin, H. (2009). *The Influence of Braking System Component Design parameters on Pedal Force and Displacement Characteristics.* Bradford Scholars.

[3] Dairou, V. (2015). *An Original Method to Predict Brake Feel.* SAE International.

[4] Day, A. (2014). Braking of road vehicles . In A. Day, *Brakin of road vehicles* (p. 460). Oxford: Elsevier.

14. Bibliography

Anonymous. (November de 2016). *Trace Parts*. Obtenido de http://www.traceparts.com/es/

Bryant, D. D. (2014). *Braking of Road Vehicles.* Bradford: University of Bradford.

Components, R. (November de 2016). *RS components*. Obtenido de http://es.rs-online.com/web/

Hecht Basch, R., Sanders, P., & Hartsock, D. (2002). *Correlation of Lining Properties with Brake Pedal Feel.* SAE International.

Larburu, N. (1989). *Prontuario de Máquinas.* Paraninfo.

Mira, H. (28 de September de 2016). *horiba mira* . Obtenido de https://www.horiba-mira.com/research/research-into-driver-pedal-feel-preference

Parts, B. A. (17 de September de 2016). *boschautoparts.com*. Obtenido de https://www.boschautoparts.com/en/auto/brakes

Reliasoft. (s.f.). *reliawiki*. Recuperado el 6 de Febrero de 2017, de reliawiki: http://reliawiki.org/index.php/Multiple_Linear_Regression_Analysis

Rover, J. -L. (2015). *Braking Systems Theory.* Birmingham.

University, B. (2014). *Braking Systems Theory.* Bradford.

Polytechnics University of Catalonia (2016). *Steering, Suspension and Braking Systems theory*. Barcelona

AMES (2017). *Selfoil Bushings*. Barcelona